Development of lightweight dual frequency/polarized microstrip antenna arrays on organic substrates for remote sensing of precipitation

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Outline

- Introduction
- Liquid Crystal Polymer (LCP) Characterization up to 110 GHz
- Dual polarized/frequency antenna arrays on LCP
- Phase Shifters using RF MEMS switches
- Conclusions/Future Work

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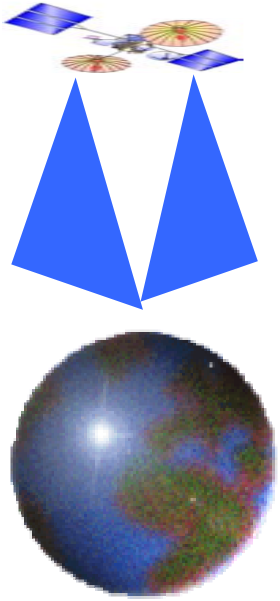
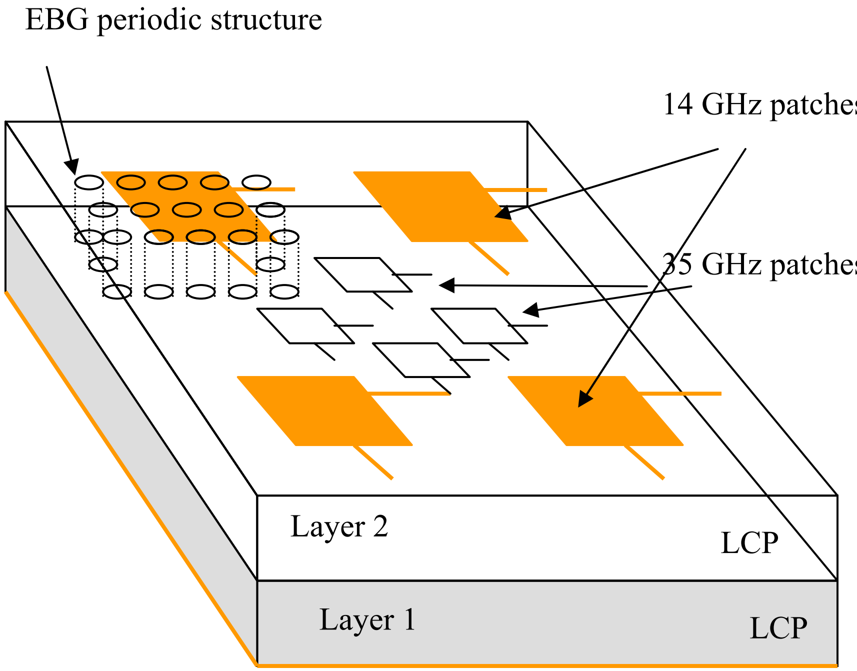
Applicability to ESE Measurements

- Accurate monitoring and measurement of the global precipitation, evaporation and cycling of water is required to better understand earth's climate system
- Dual frequency/polarization radiometers are necessary to monitor precipitation patterns
- Antenna and RF front ends that have low cost, low mass, electronic scanning capabilities and are easily deployed, are preferred
- Develop novel dual frequency/polarization array and associated electronics based on System-on-a-Package (SOP) approach



Proposed Technology

- Investigate multi-layer Liquid Crystal Polymer Technology (LCP)
- Two sets of microstrip antennas on different layers: 14 GHz array on top layer, 35 GHz array on bottom layer
- Planar and vertical feeding networks and interconnects
- Implementation of Electromagnetic Band Gap (EBG) structures for minimization of cross-talk if needed
- Usage of RF MEMS phase shifters for electronic scanning



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Why LCP?

- Electrically: ε_r=2.9, tan δ=0.002-0.003
- Its near hermetic nature suits it as both a mm-wave substrate and package (~ glass in water transmission)
- LCP films from 25 – 200 µm thick can be conveniently laminated for multilayer structures used in system on package (SOP) designs
- $Low cost (~ 2-3 times more expensive than FR4)$
- LCP is flexible, and antennas fabricated on it may be rolled or molded into desired shapes
- Best mix of performance, mechanical integration compatibility, and economic viability

Integration Compatibility

- Transverse coefficient of thermal expansion (CTE) may be engineered to match semiconductors, Cu, and Au

- Two types of LCP with the same electrical properties but different melting temperatures are available. This allows separate “bond” and “core” layers in the lamination process for multi-layer structures
- Low moisture absorption <0.02%

CTE (ppm/ °C)

LCP = 0 - 30 (engr’d)

Cu = 16.8

Au = 14.3

Si = 4.2

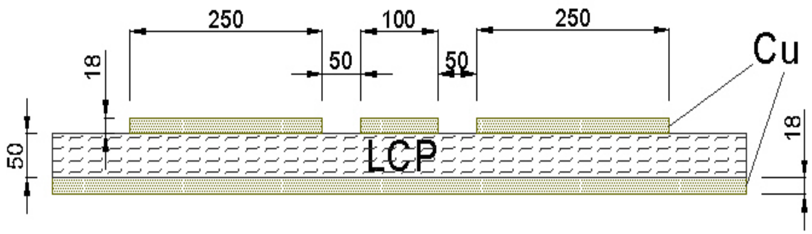
GaAs = 5.8

SiGe = 3.4 - 5

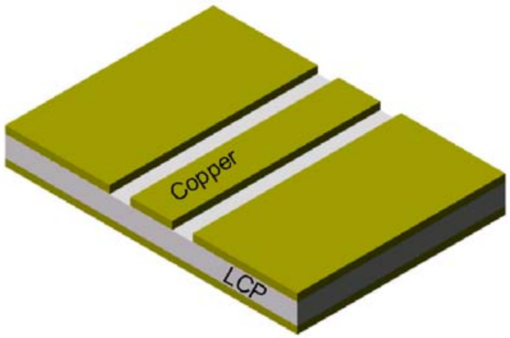
- Core
- TYPE I (335 °C)
- Bond
- TYPE II (285 °C)

Conductor Backed CPW

- A conductor-backed coplanar waveguide (CBCPW) design is selected in order to measure LCP's dielectric performance up to the maximum VNA capability of 110 GHz



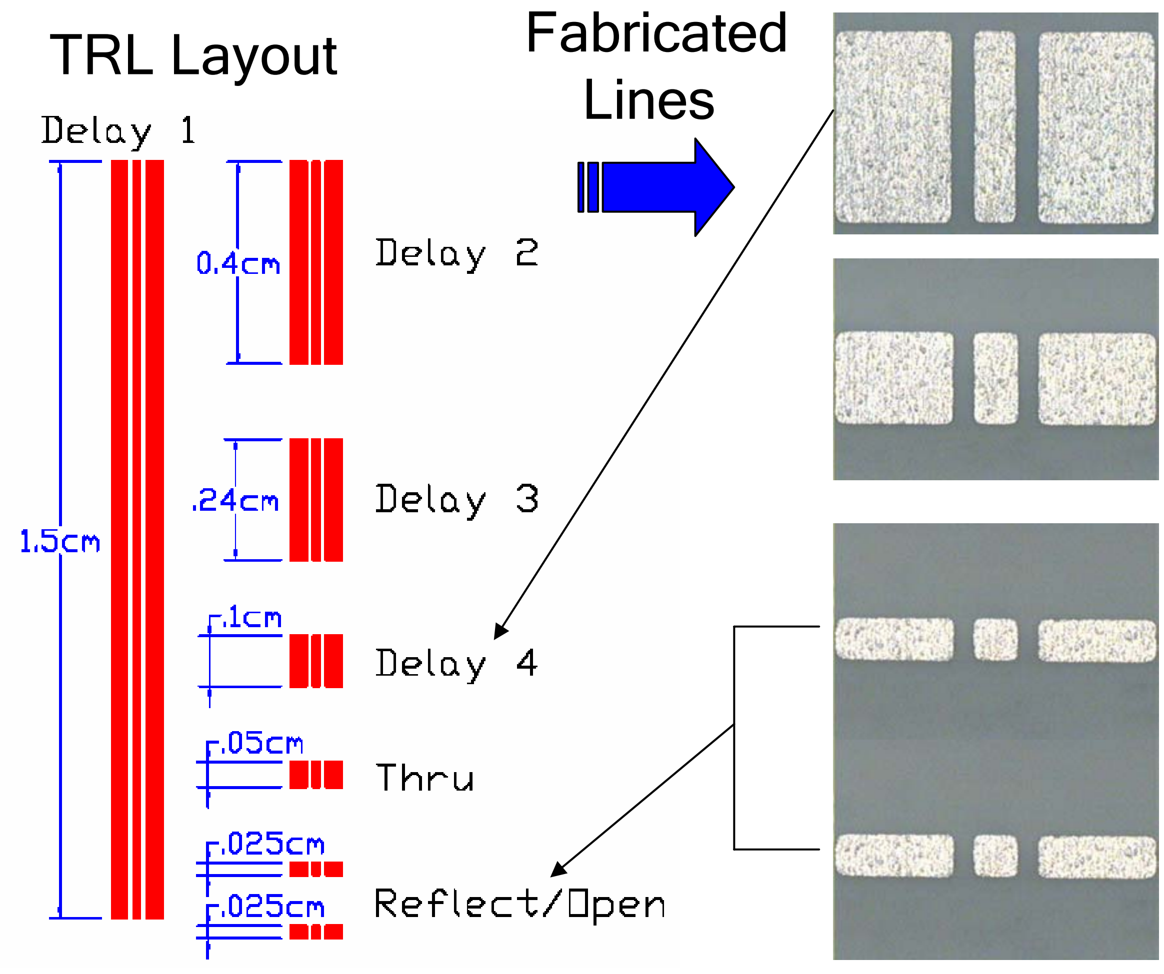
- The designed line is close to 50 Ω to minimize reflections (Dim: μm)



- Lines fabricated to the NIST TRL specifications include:

Line Type	Line Length
Delay 1	1.50 cm
Delay 2	0.40 cm
Delay 3	0.24 cm
Delay 4	0.10 cm
Thru	0.05 cm
Reflect/Open	0.025 cm

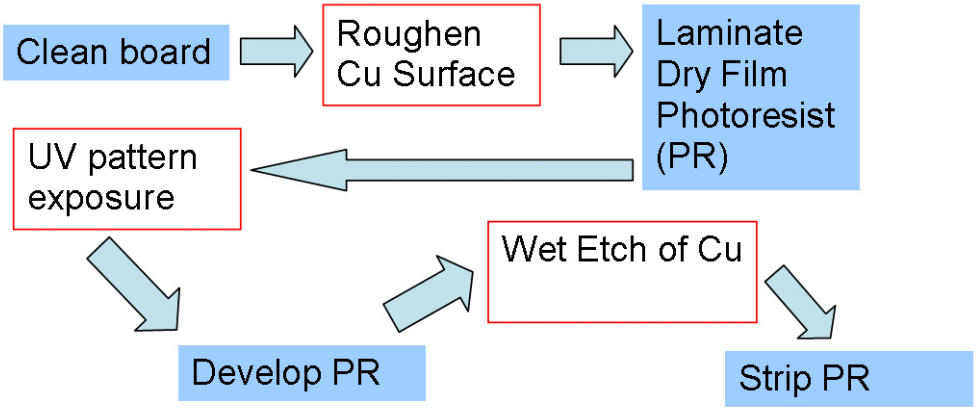
CBCPW (cont.)



TRL Layout
Fabricated Lines
Delay 1
1.5cm
0.4cm
Delay 2
.24cm
Delay 3
.1cm
Delay 4
.05cm
Thru
.025cm
.025cm
Reflect/Open

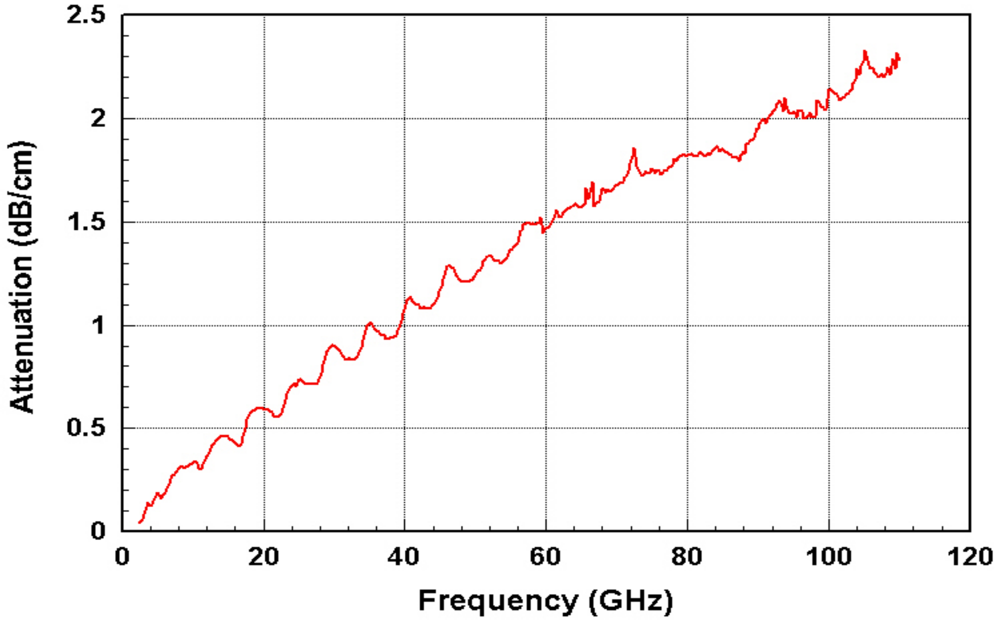
Fabrication/TRL Basics

- Patterning of circuits was done using a standard photo-lithographic process
- 15 4” x 4” boards, each with 48 complete sets of TRL lines were fabricated



- Inputs to the NIST Multical algorithm are the line types and lengths along with the measured data from those lines
- The algorithm uses the phase differences from the multiple transmission line segments in order to calibrate across a wide frequency range
- Effects of the probes are removed and additional characteristics are evaluated

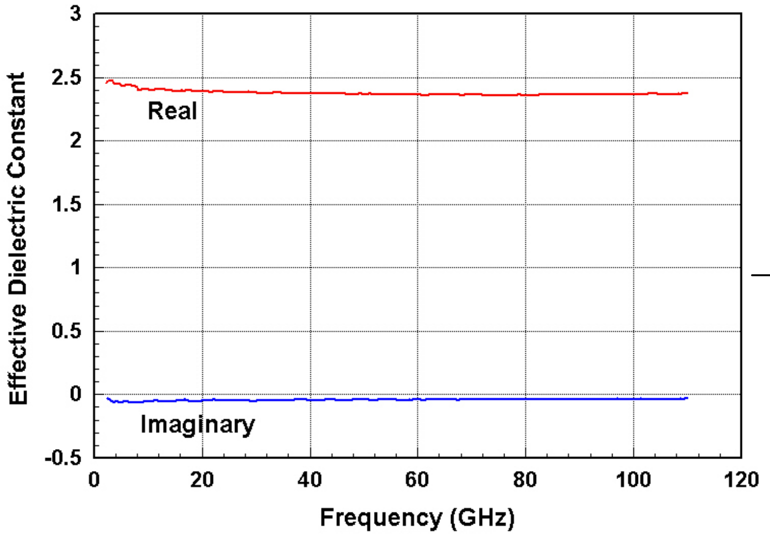
Measurement Results

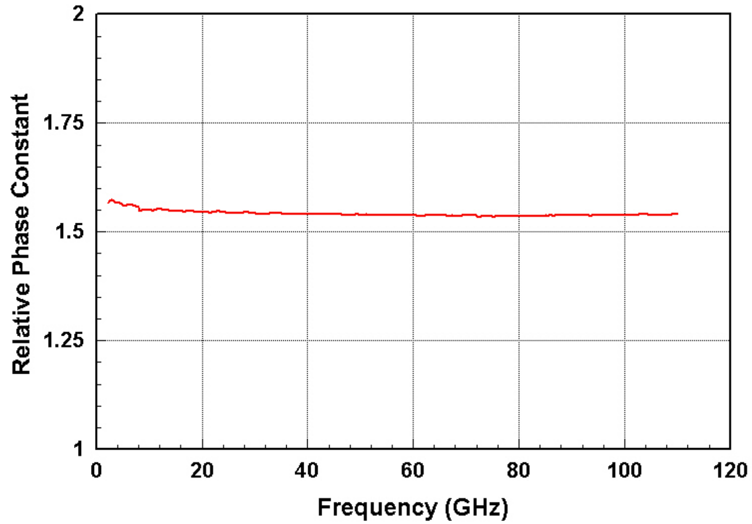


Frequency (GHz)	Attenuation (dB/cm)
5.8	0.17
35	1.01
60	1.47
77	1.75
94	2.07
110	2.29

- Attenuation characteristics are exceptional through the W-band (50 μm substrate)
- Applications in many different frequency bands could benefit from RF designs integrated on LCP substrates and packages

Measured Results





- The real part of ε_{eff} varies by 0.12, while for a vast majority of the frequency range ε_{eff} = 2.36 - 2.37.
  - This reveals an almost pure TEM mode of propagation over the entire frequency range.
- The relative phase constant varies by 0.04 but is almost constant at 1.54 from 20 – 110 GHz. Again this implies constant propagation characteristics.

CPW on 200 μm LCP Substrate

- A CPW (not conductor-backed) on a 200 μm LCP substrate is fabricated and measured on a foam spacer.
- Most of the field propagates through the LCP dielectric with minimal interaction from the foam spacer.
- The attenuation curve is matched to theoretical equations and the loss tangent is approximated

Curve Matching

The CPW measured attenuation curve is curve matched using a least squares algorithm. Individual loss terms are approximated using the following theoretical assumptions.

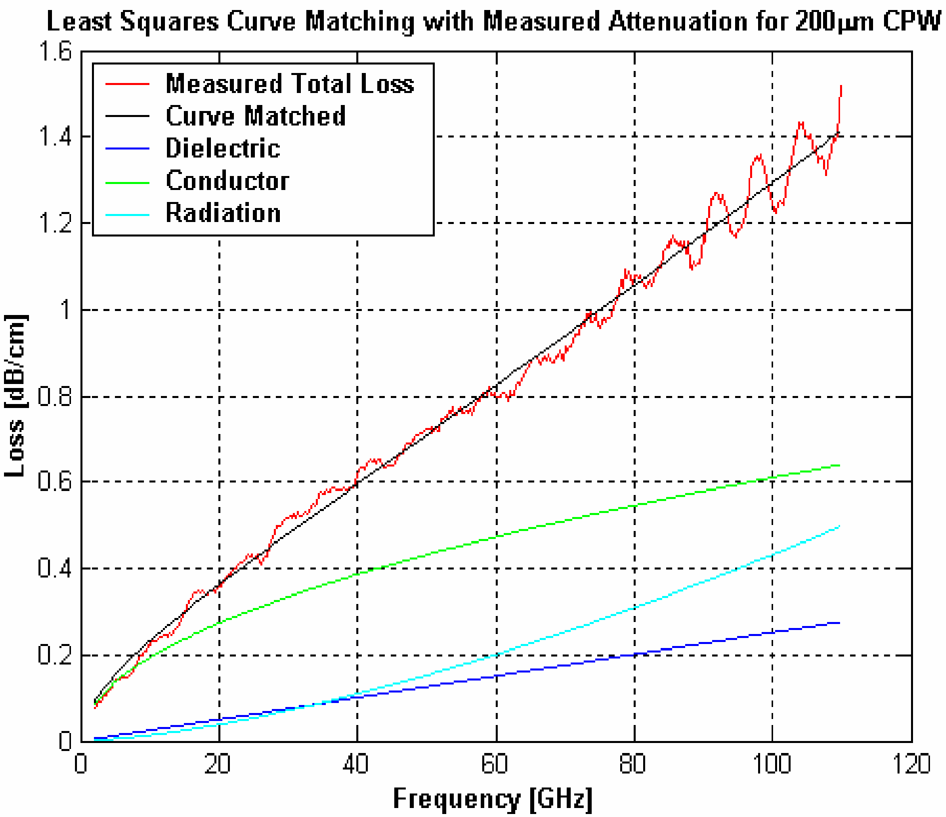
$$\alpha_{tot} = a_1 f + a_2 f^{\frac{1}{2}} + a_3 f^{\frac{3}{2}}$$

where

Dielectric loss ~ $a_1 f$

Conductor loss ~ $a_2 f^{\frac{1}{2}}$

Radiation loss ~ $a_3 f^{\frac{3}{2}}$

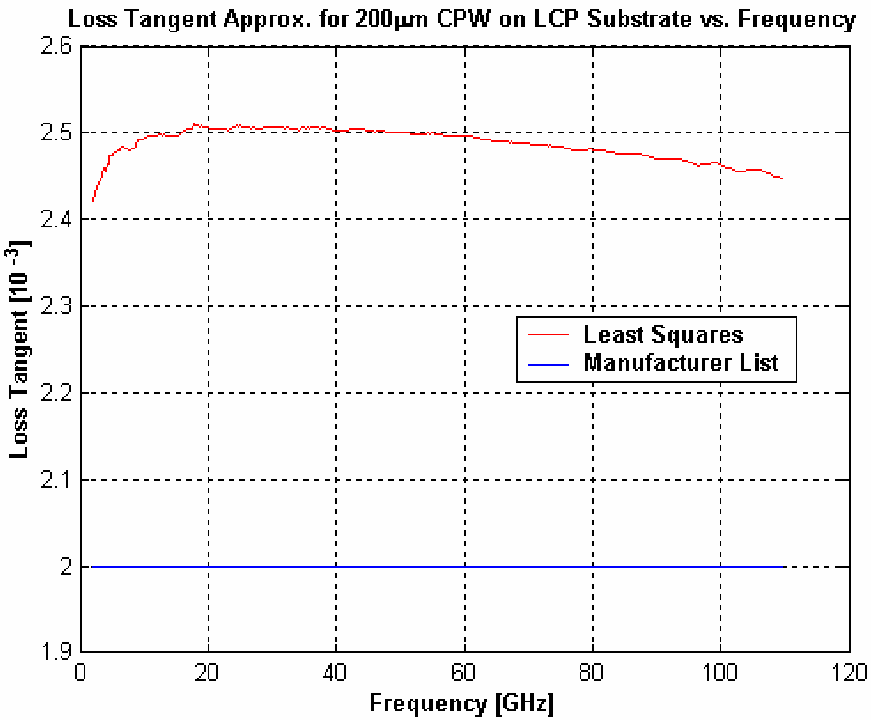


Curve Matching (cont.)

From the extracted dielectric loss contribution, the following equation can be used to obtain the approximated dielectric loss plot shown.

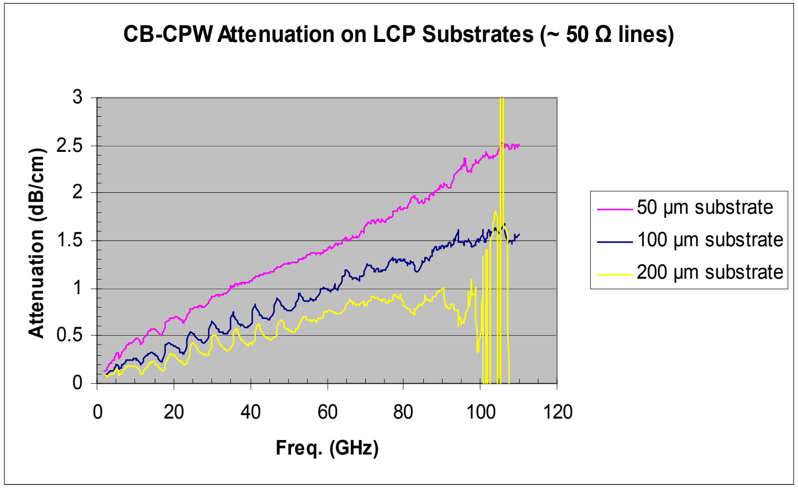
$$\tan\delta = \frac{\alpha_d c_o \sqrt{\varepsilon_{eff}}\left(\varepsilon_r - 1\right)}{\pi f \varepsilon_r \left(\varepsilon_{eff} - 1\right)}$$

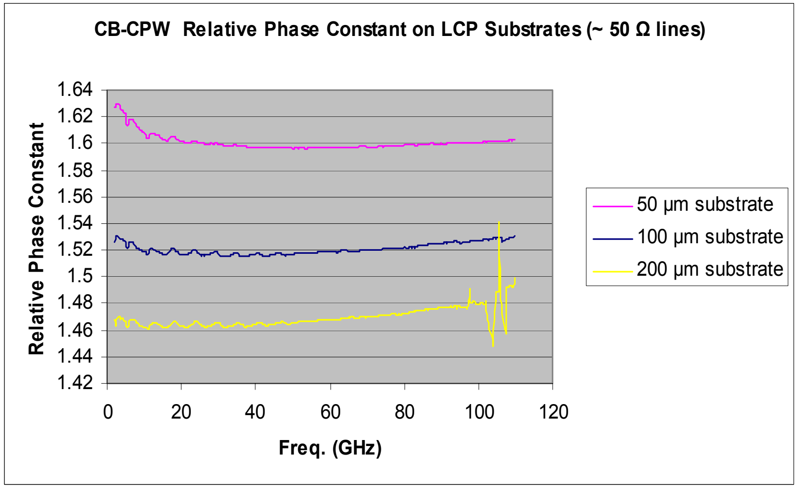
α_d = extracted dielectric loss [Np/m]
ε_r = listed dielectric constant = 2.9
ε_{eff} = measured effective diel. constant
c_o = speed of light in free space
f = frequency

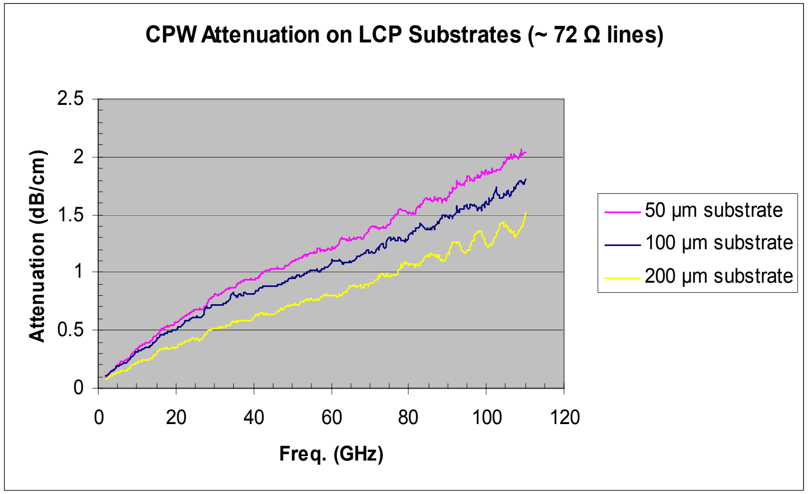


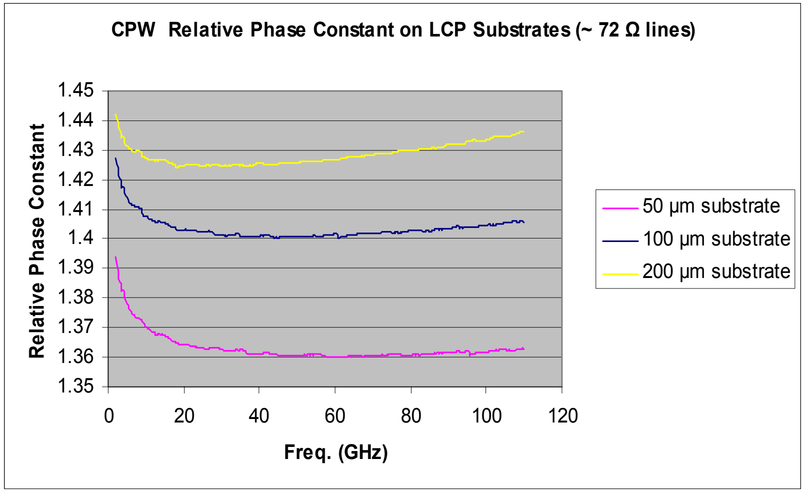
A broadband loss tangent (tanδ)~0.0025 is approximated. This compares similarly to the manufacturer's list value of 0.002. Further testing of this method is necessary to ensure accuracy.

CB-CPW & CPW Attenuation and Relative Phase Constant









LCP Performance vs. other substrates

- Liquid Crystal Polymer (LCP) measurements on coplanar waveguides (CPWs) of different substrate thicknesses show attenuation characteristics similar to GaAs

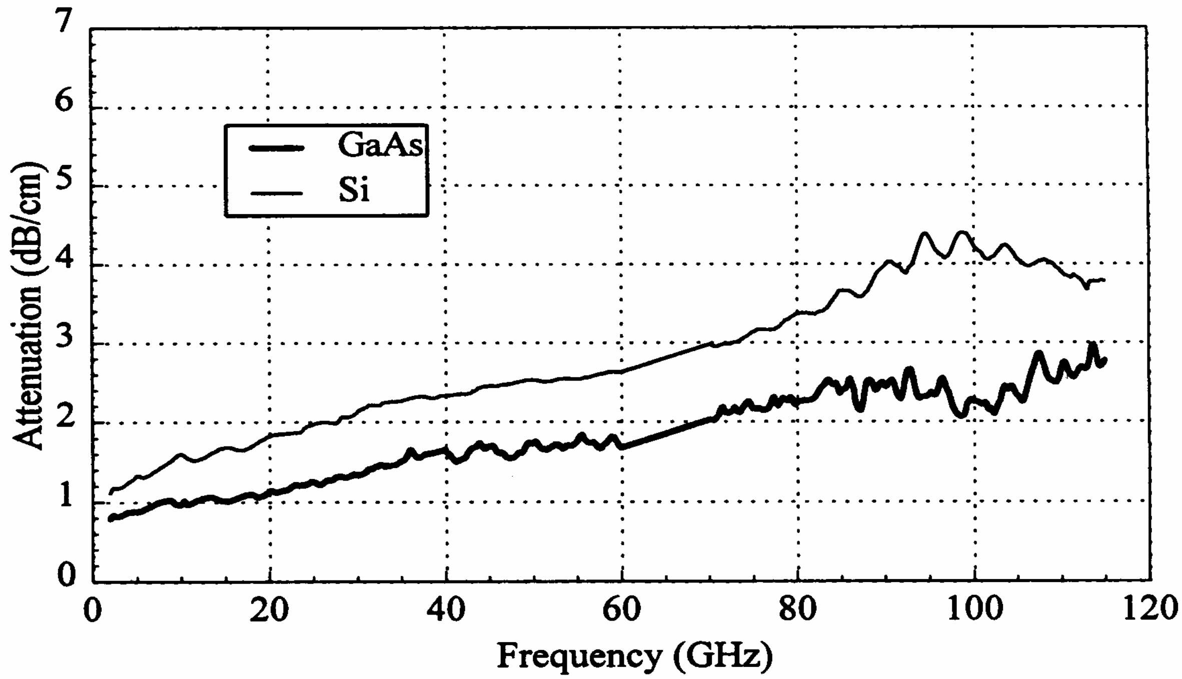


Figure 3-6 Measured attenuation in dB/cm of a FGC transmission lines on a GaAs and a Si substrate. The line dimensions are w = 50 µm, s = 45 µm, and w_g = 160 µm in each case.

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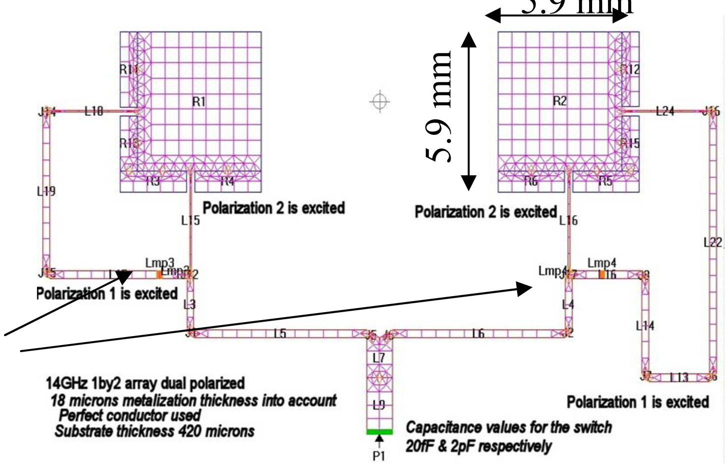
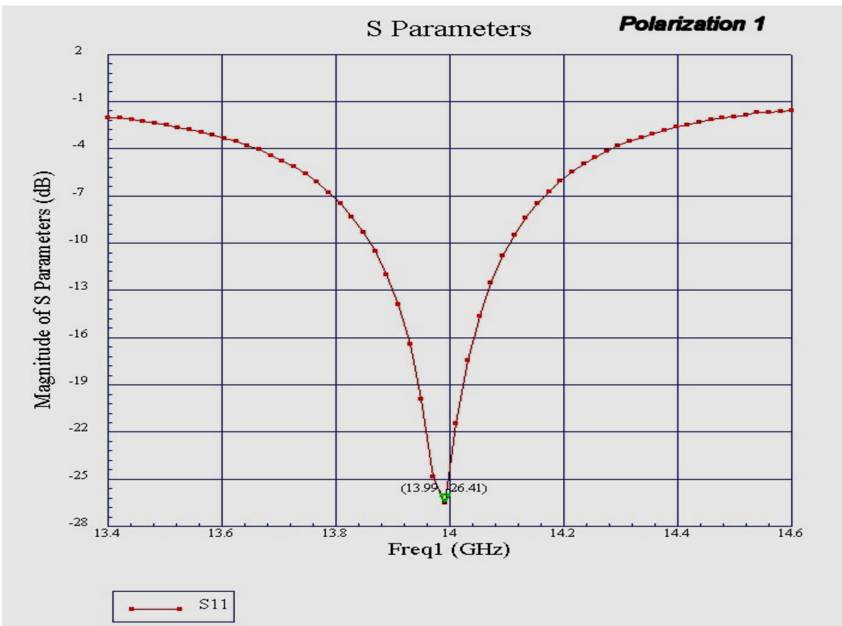
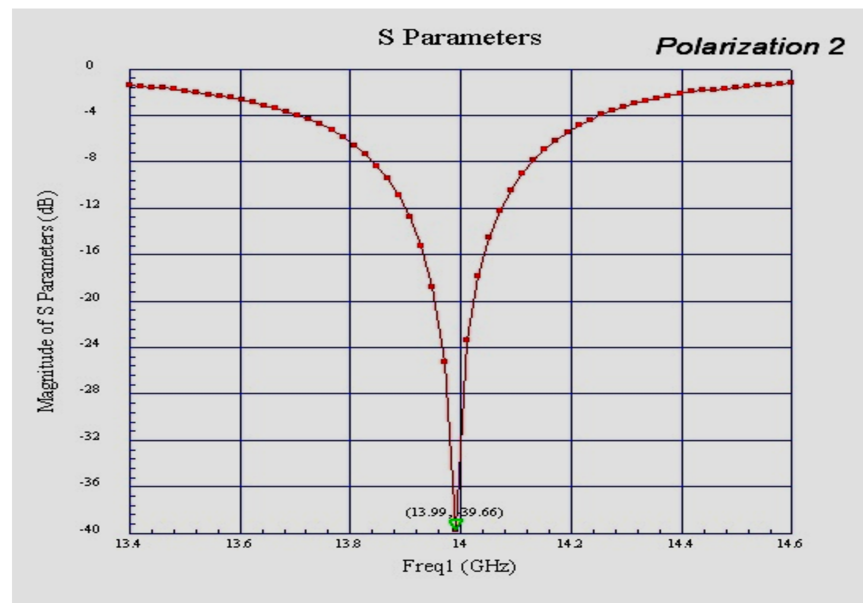
14 GHz 1x2 Array

• The simulated structure with the introduced capacitance from the single-pole double throw (SPDT) MEMS switch.
(20 fF & 2pF relatively and 0.2 ohms real resistance) *EMPicasso* software

Switch

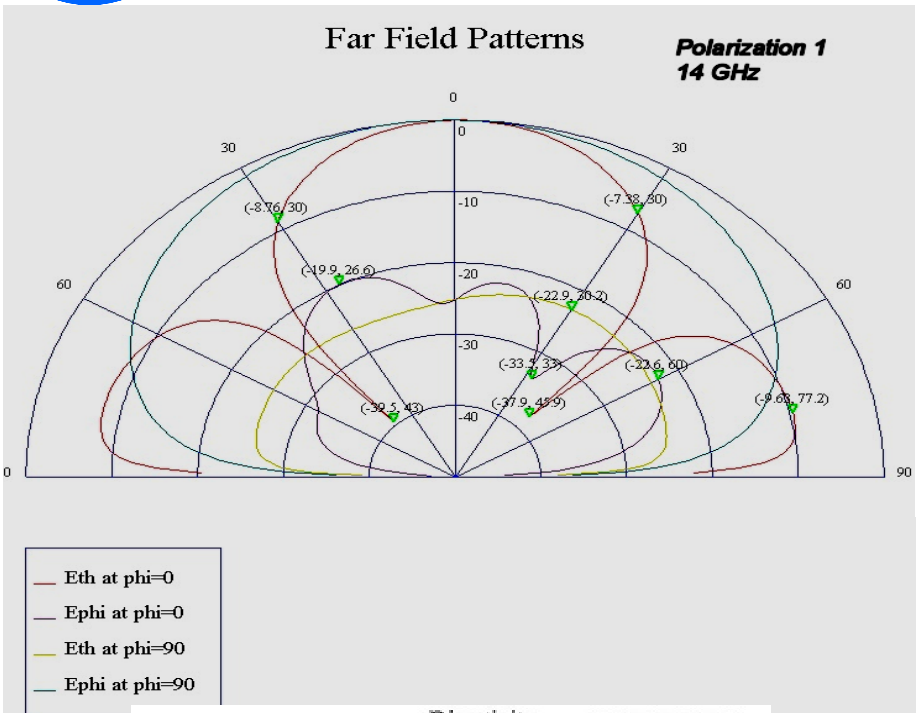


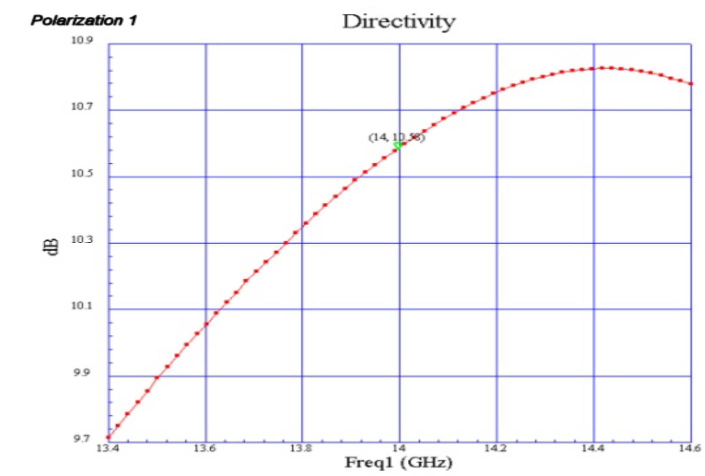


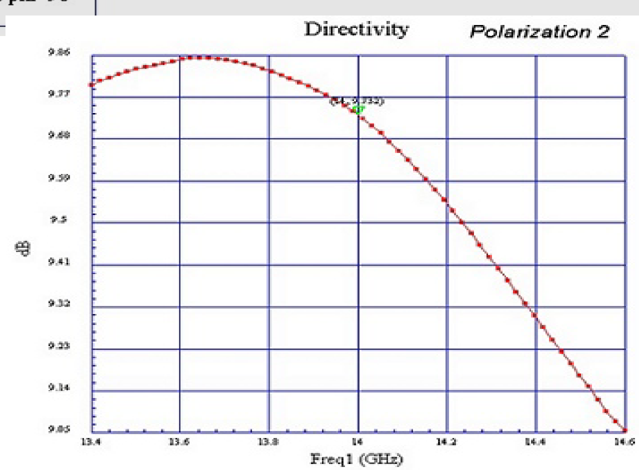


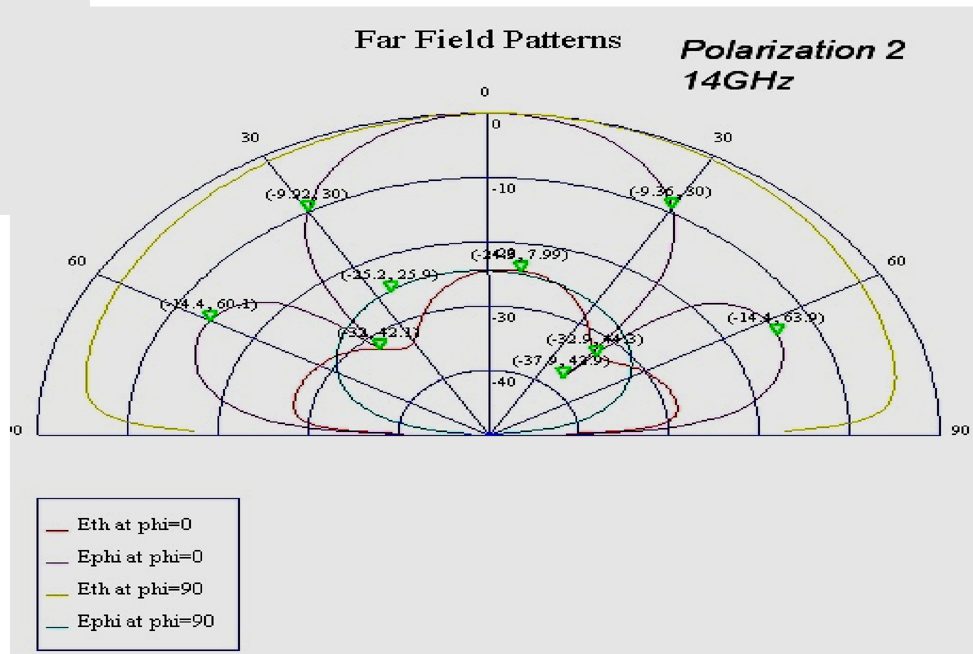
Simulated S-parameters for both polarizations

14 GHz 1x2 Array Patterns





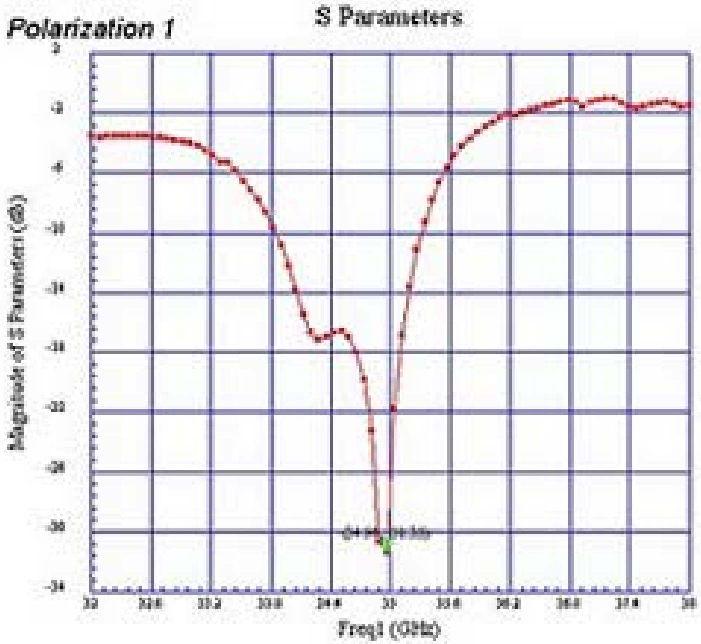


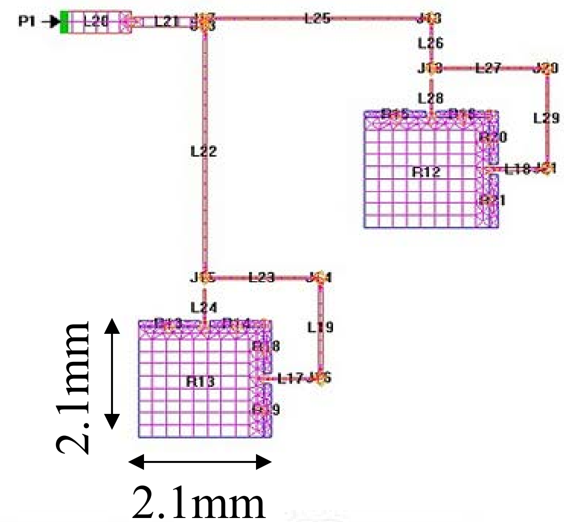


14 GHz 1x2 Array Results

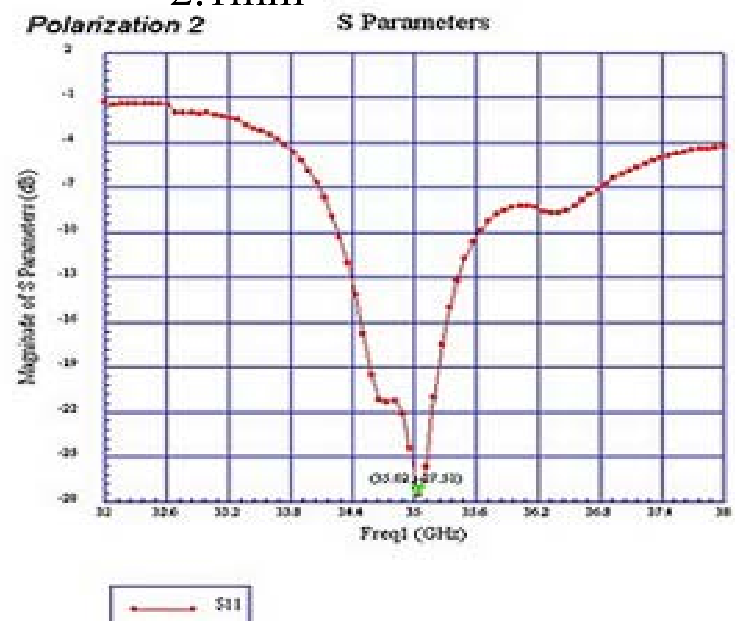
- Return loss > 25 dB for both polarizations
- The position of the lumped elements affects the return loss response
- Side lobes for polarization 1 are around 5 dB higher than lobes of polarization 2
- Directivity is about 1 dB higher for polarization 1
- The beamwidth at xz-plane (phi=0) is 35.32 degrees for polarization 1 & 24.66 degrees for polarization 2
- At yz-plane (phi=90), we got 74.48 degrees for polarization 1 & 68.48 for polarization 2

35 GHz (2x1) Antenna Array

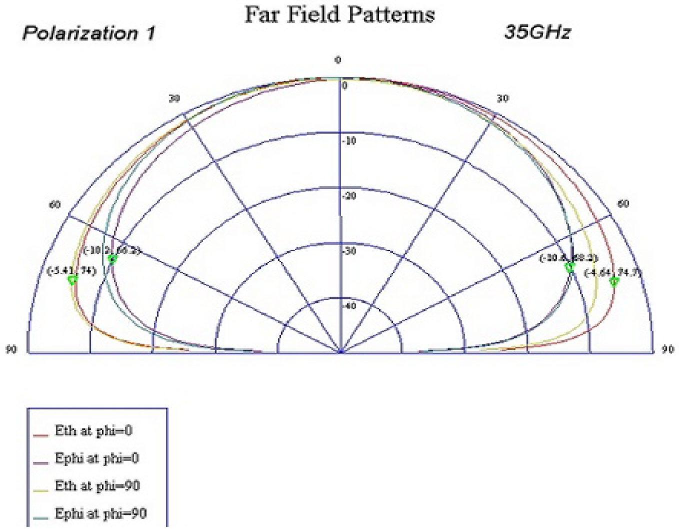


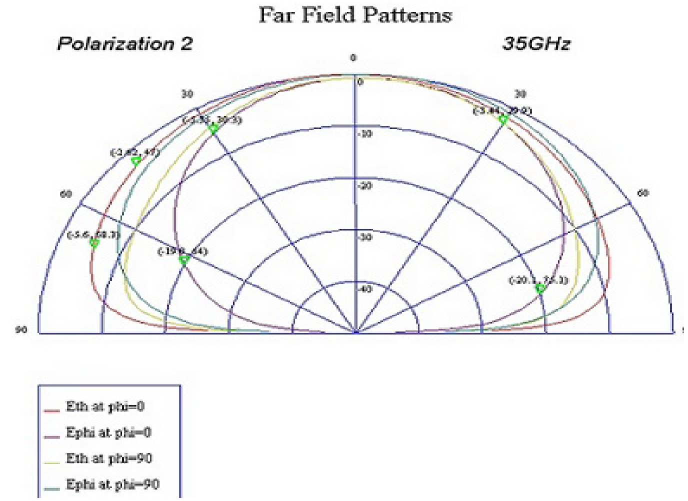


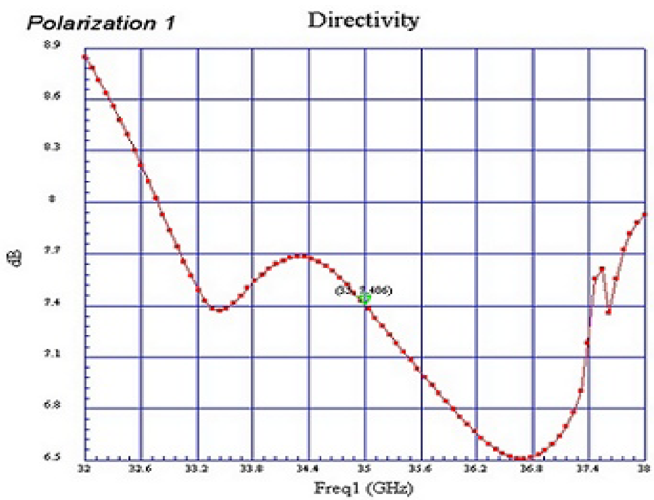
An 1x2 array at 35 GHz on 200 microns LCP with another 220 micron LCP superstrate

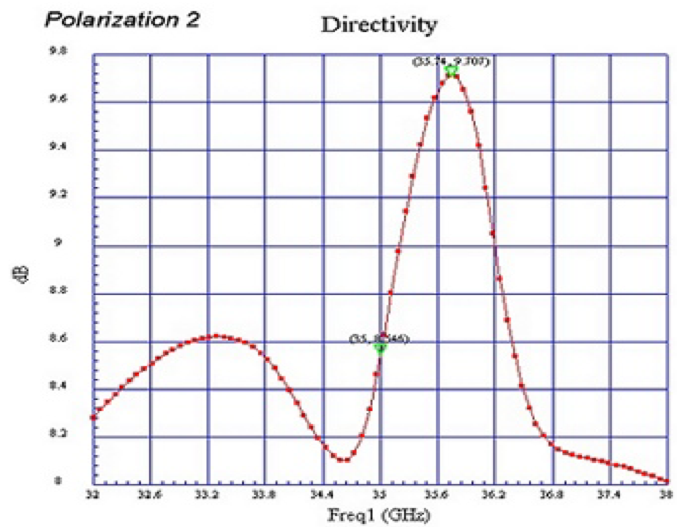


35 GHz Far field and Directivity







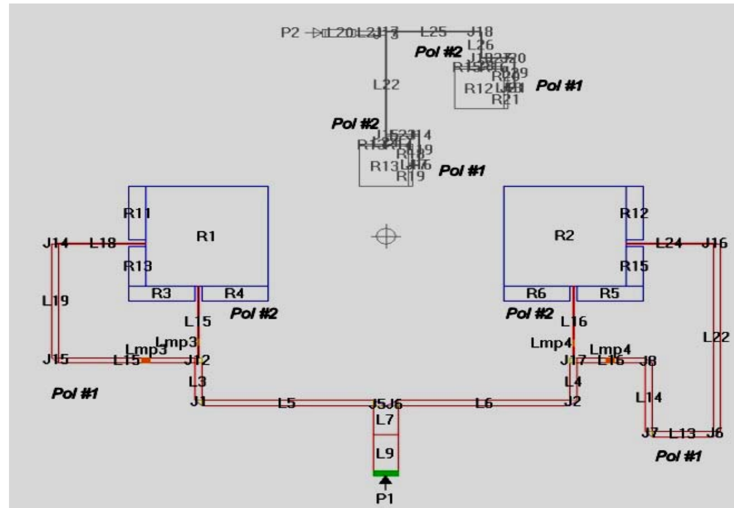


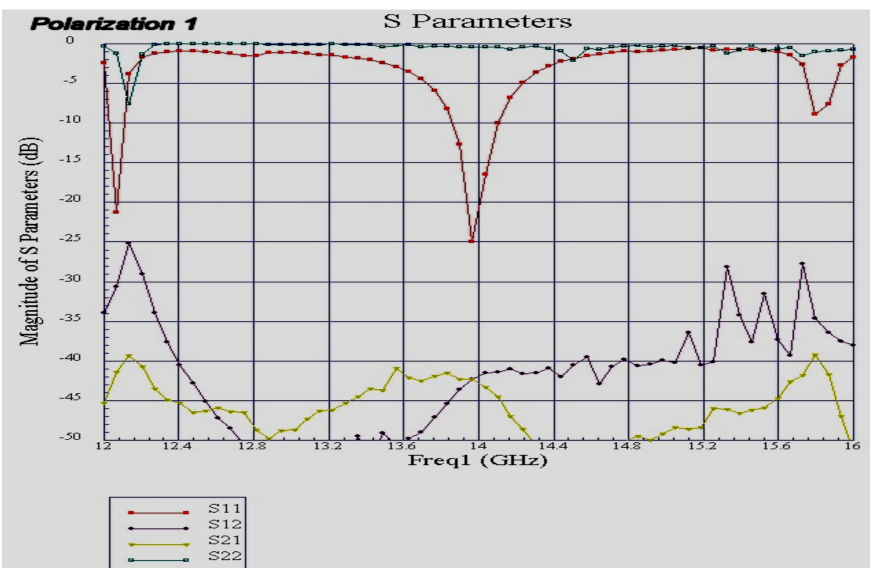
35 GHz 1x2 Array Results

- No significant side lobes although the distance between the two patches is more than a wavelength (λg)
- Superstrate makes the array more broadband
- The directivity we achieved is 7.4 dB for polarization 1 & 8.5 dB for polarization 2. This is significantly lower than the 14 GHz array due to smaller substrate thickness and the superstrate
- The beamwidth at xz-plane (phi=0) is 79.8 degrees for polarization 1 & 62.72 degrees for polarization 2
- At yz-plane (phi=90), we got 60.4 degrees for polarization 1 & 71.22 for polarization 2

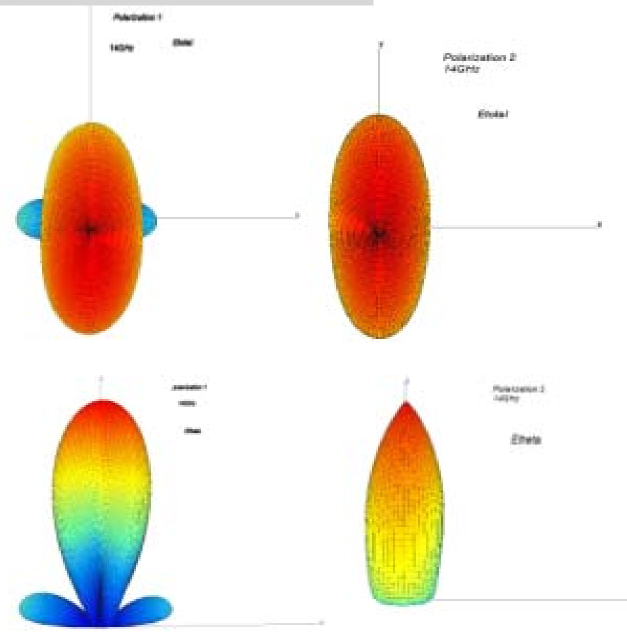
The total 14/35 GHz array

- At 14GHz the array works close to the desired way.
- The coupling between the two layers is low at this frequency.
- There isn't any interference with the "sandwiched" array





The s-parameter response. Low coupling between the two layers

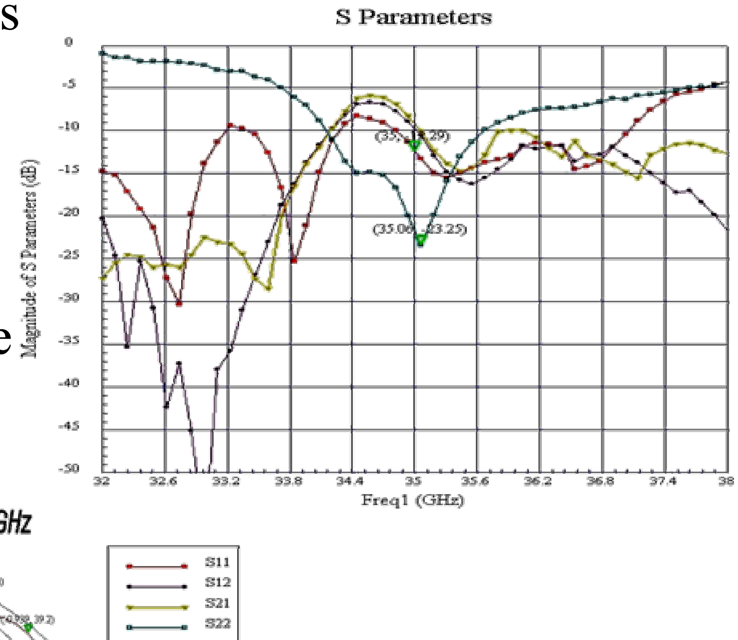


Etotal and Etheta for both polarizations At xy and xz-planes relatively at 14GHz

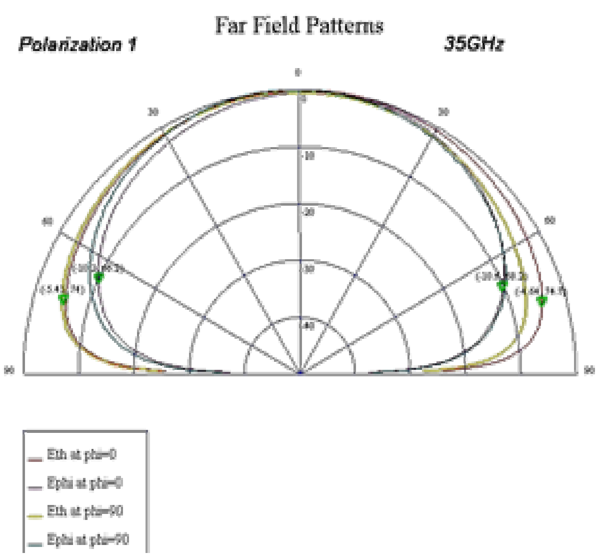
Design Challenges

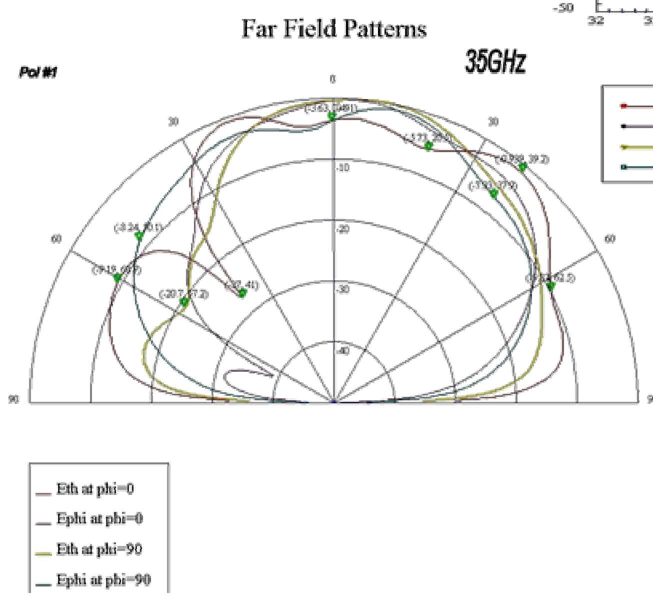
• Destructive interference of the two antennas layers causes a lot of diffraction on the 35GHz array radiation pattern. We are working to eliminate this effect.

• High coupling occurs at the high frequency (35GHz) between the two layers. An EBG structure may be needed to reduce it.



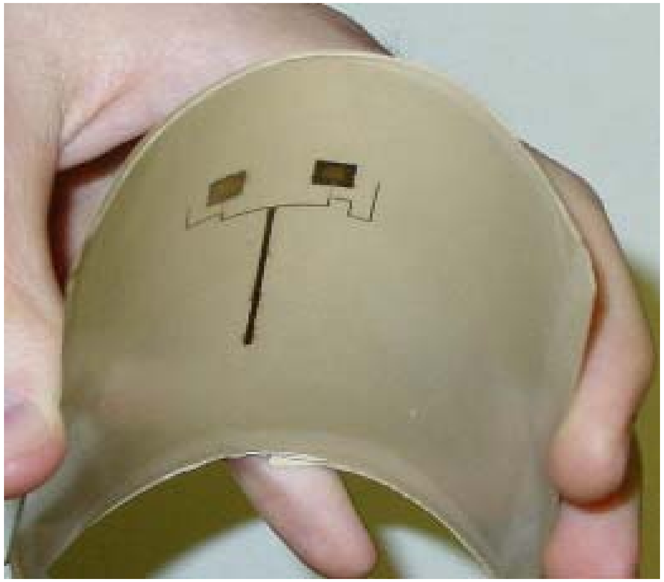
High coupling between the two layers around 35 GHz





The far field pattern at 35GHz and the effect of the above 14GHz array

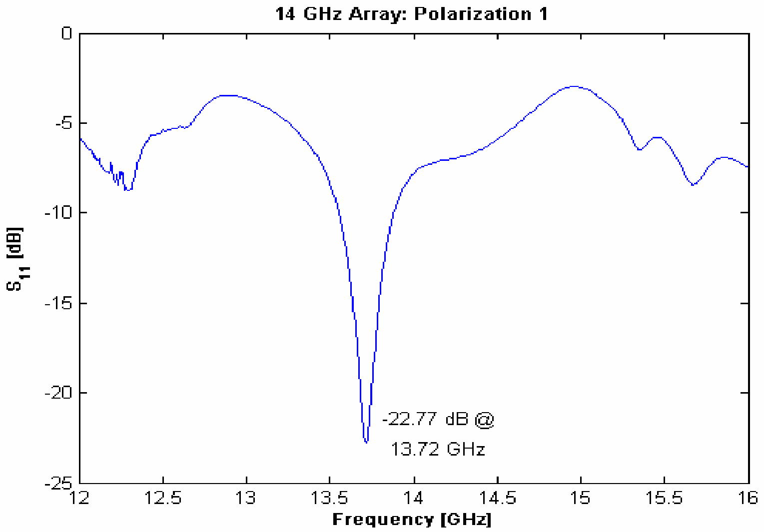
LCP Flexibility

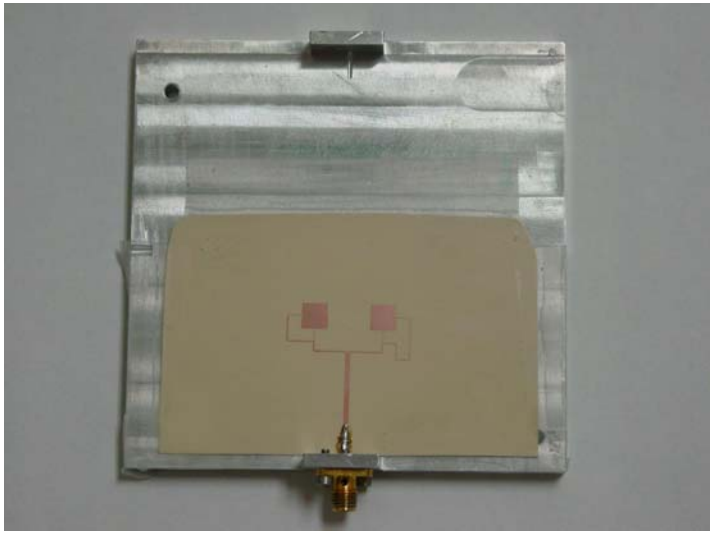


- Flexibility demonstration of a 14 GHz 1x2 antenna array on 425 micron LCP substrate

Measured Results For Antennas on LCP

• A 14 GHz 2x1 antenna array on a 425 micron LCP substrate has been fabricated and measured. S_{11} is -23dB at 13.72 GHz for polarization #1 (side feeds)



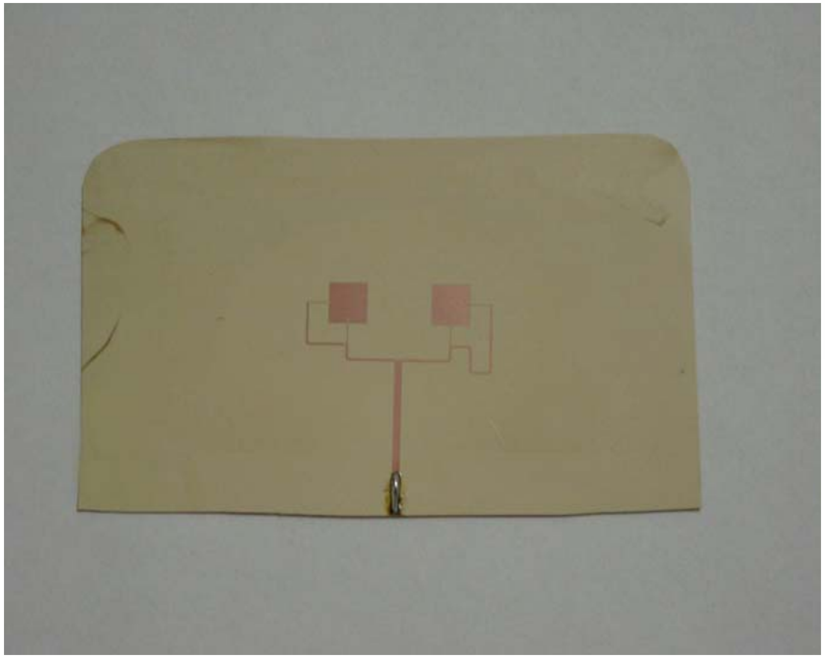


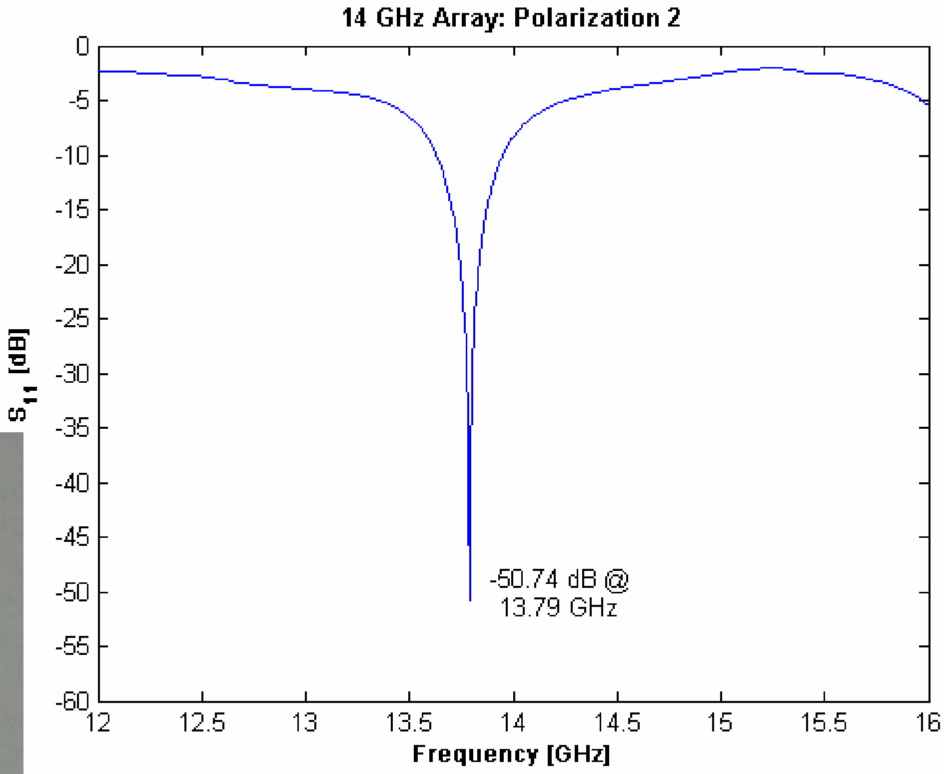
• Utilizing MEMS switches on LCP will enable switchable phased array antennas

• Multi-layer LCP substrates with antennas and filters vertically integrated will form RF front-end packages

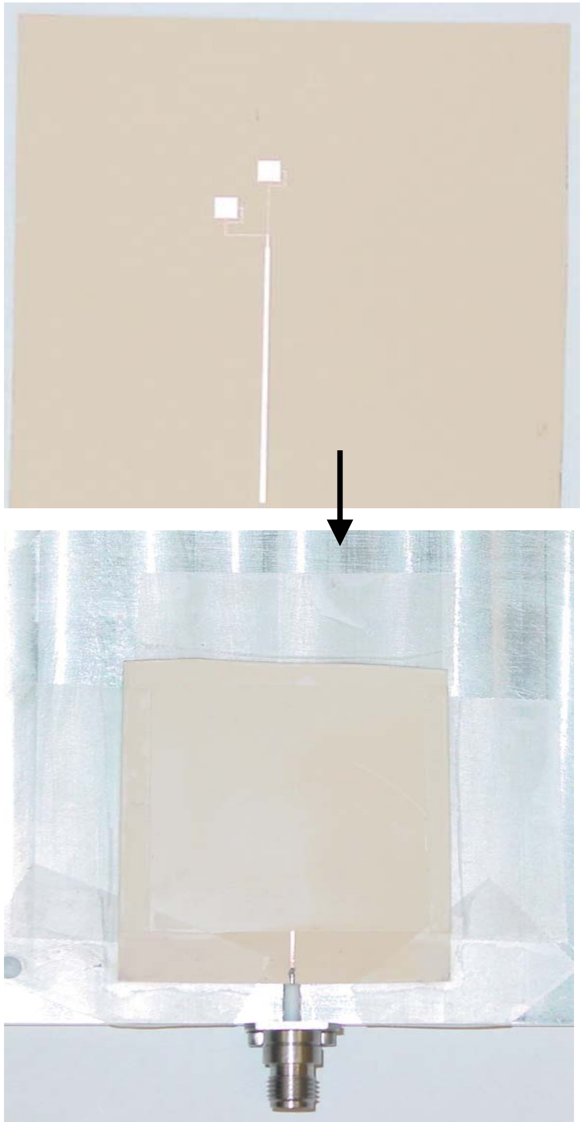
Measured Results For Antennas on LCP

- S_{11} is -51dB at 13.79 GHz for polarization #2 (bottom feeds)



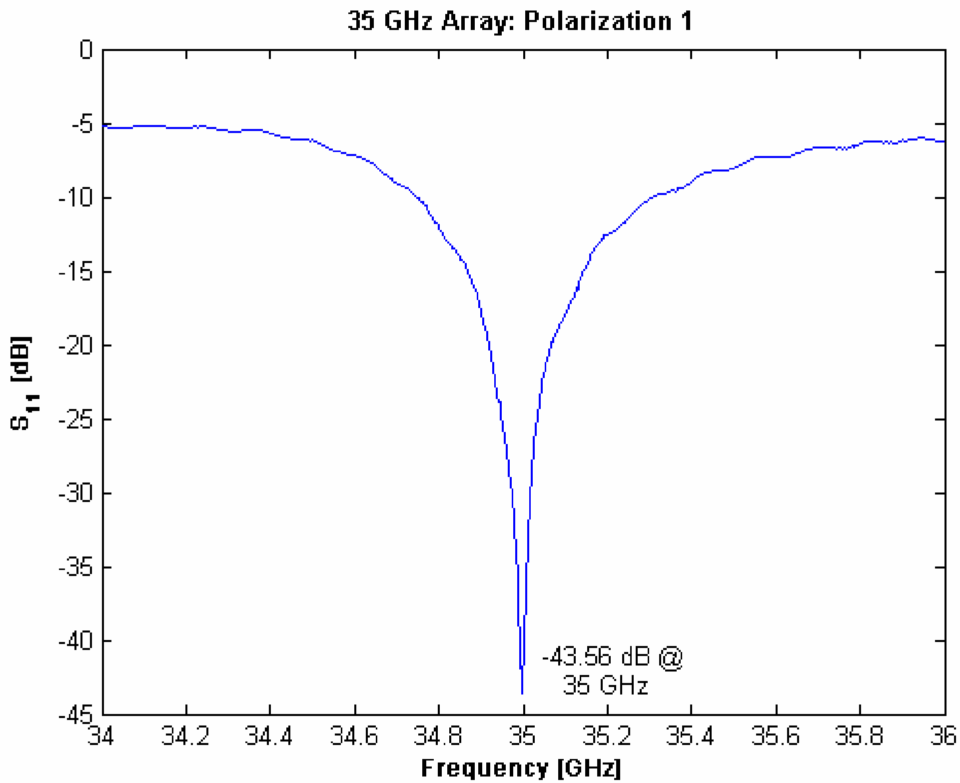


Measured Results For Antennas on LCP

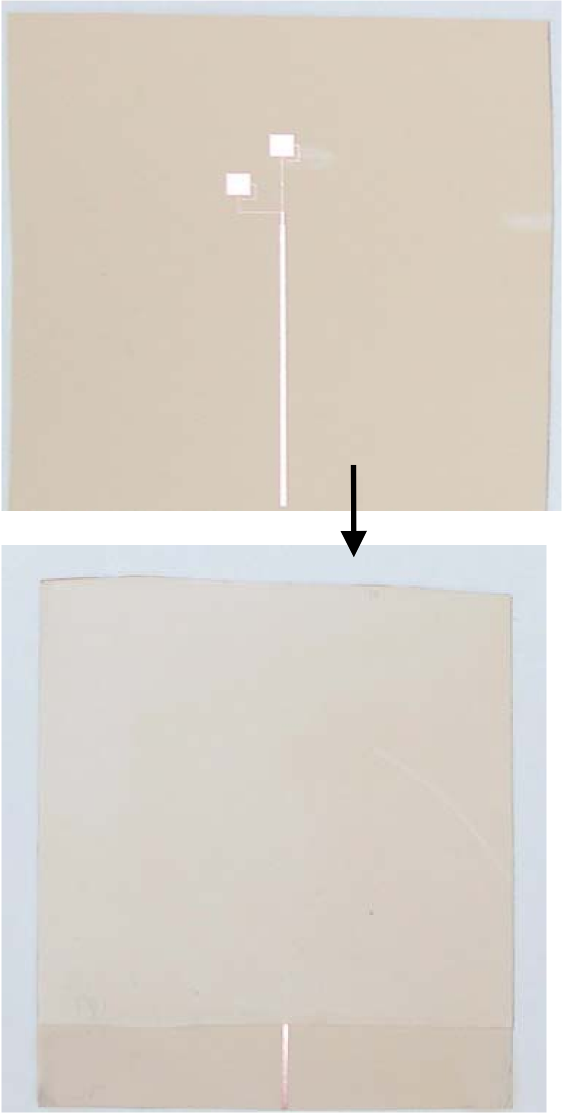


•Laminated a 225 micron LCP superstrate on top of the 35 GHz antenna array.

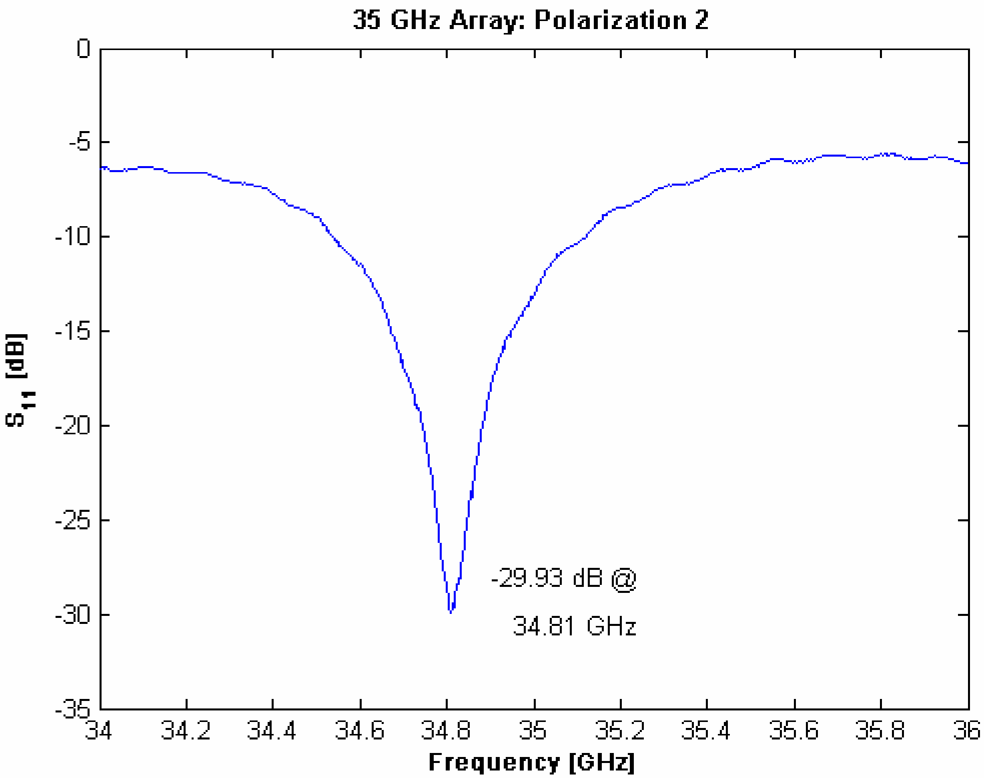
•S_{11} is -44dB at 35 GHz for polarization #1 (side feeds)



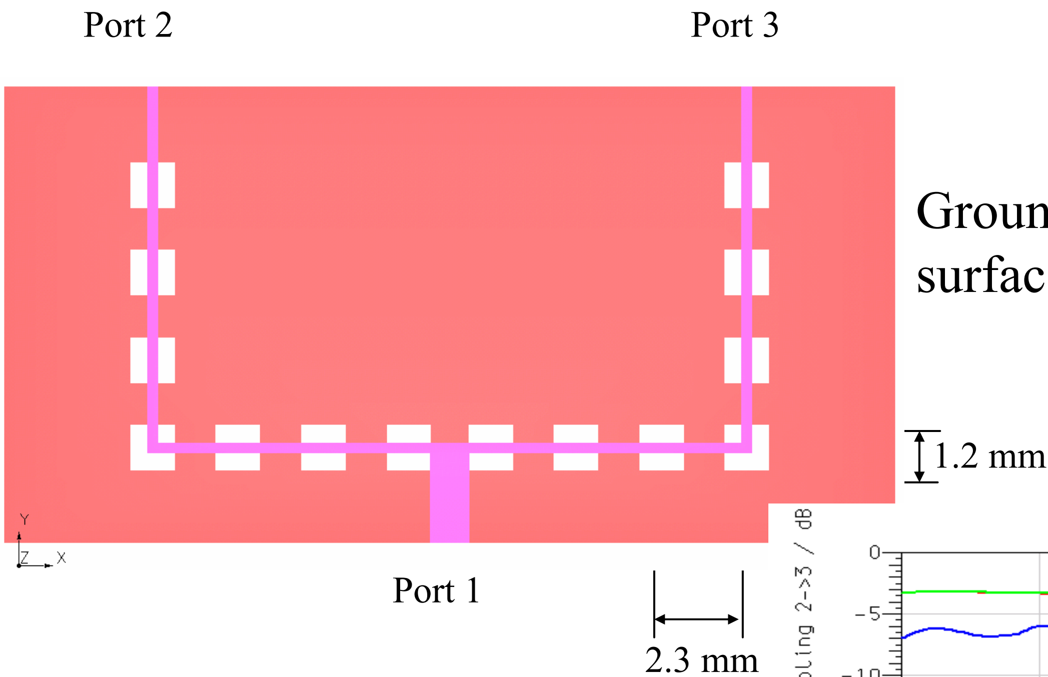
Measured Results For Antennas on LCP



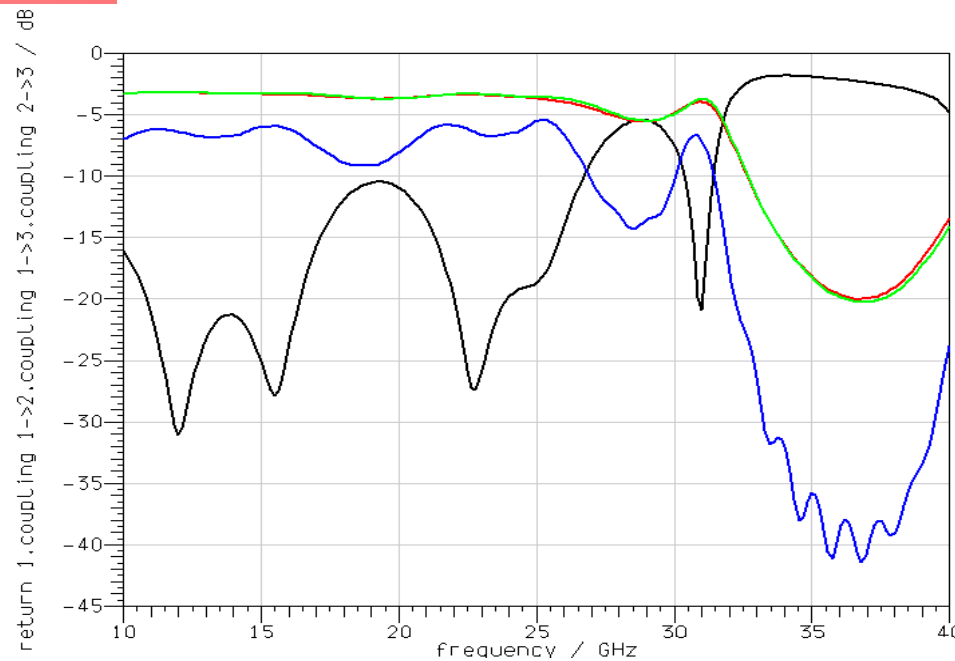
- Laminated a 225 micron LCP superstrate on top of the 35 GHz antenna array.
- S_{11} is –30 dB at 34.8 GHz for polarization #2 (bottom feeds)



EBG Structures



Ground-patterned EBG structure for surface-wave suppression around 35 GHz



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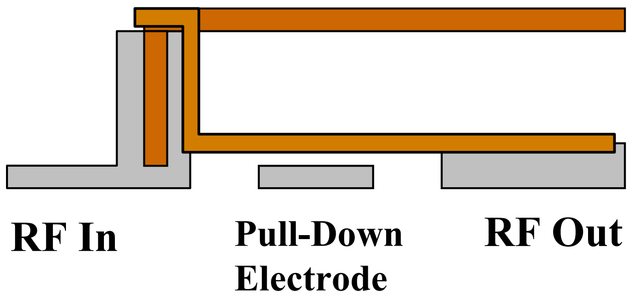
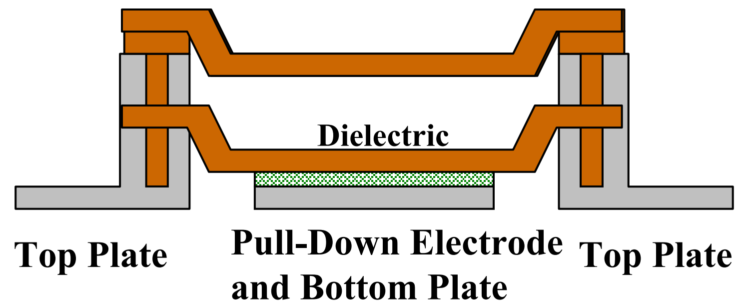
RF MEMS Switches



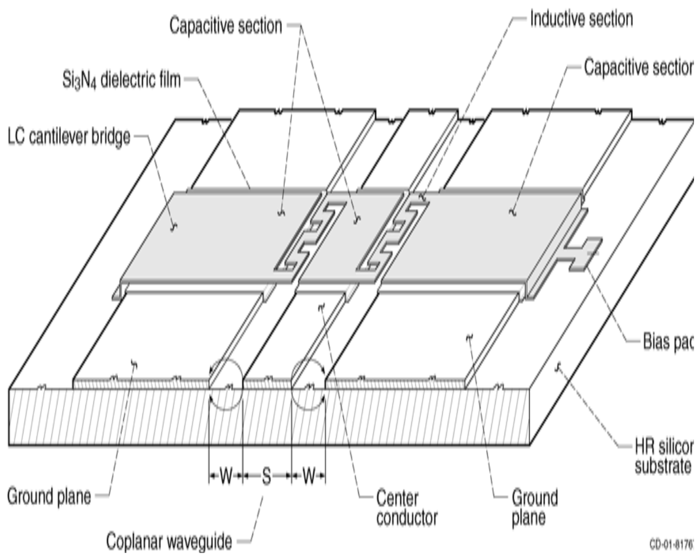
Cantilever beam

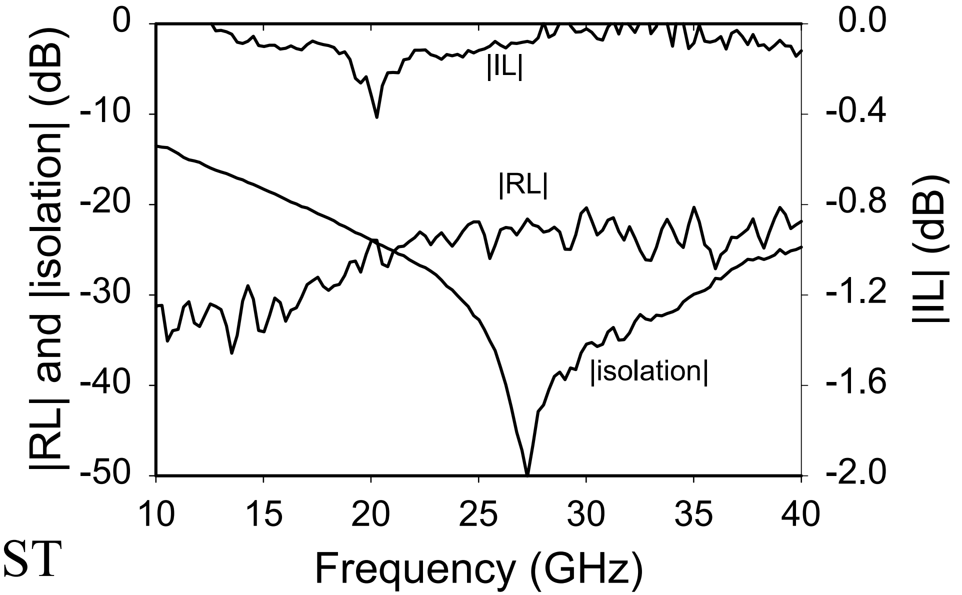


Air-bridge

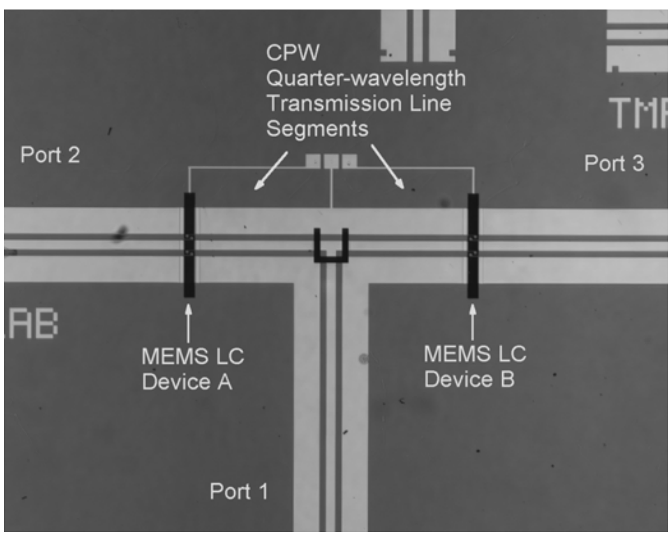
- Electrostatic actuation (5-60V)
- Low loss (up to W-band) and low cost
- High linearity – no distortion (IIP_3>60 dBm)
- No power consumption
- Switching time 1-20 μs
- IC fabrication compatible

RF MEMS Switches on High-ρ Silicon

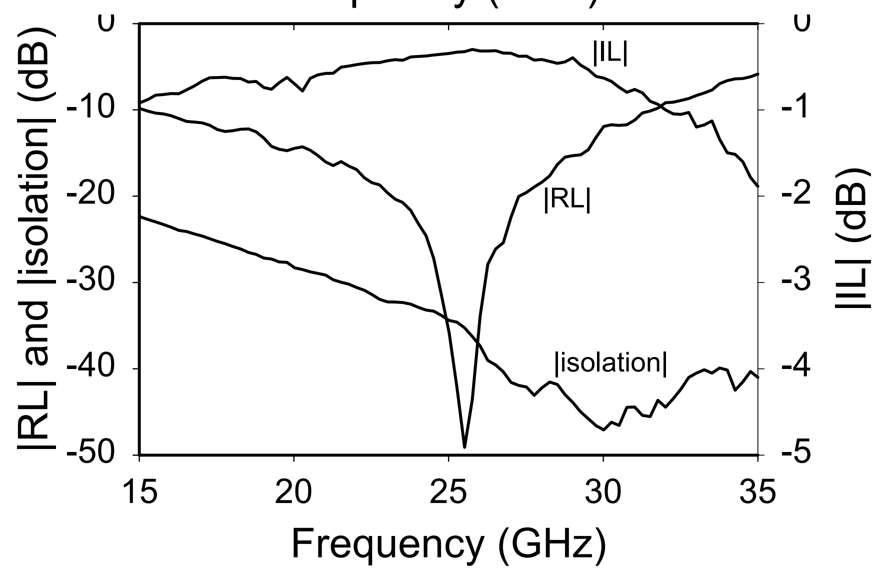




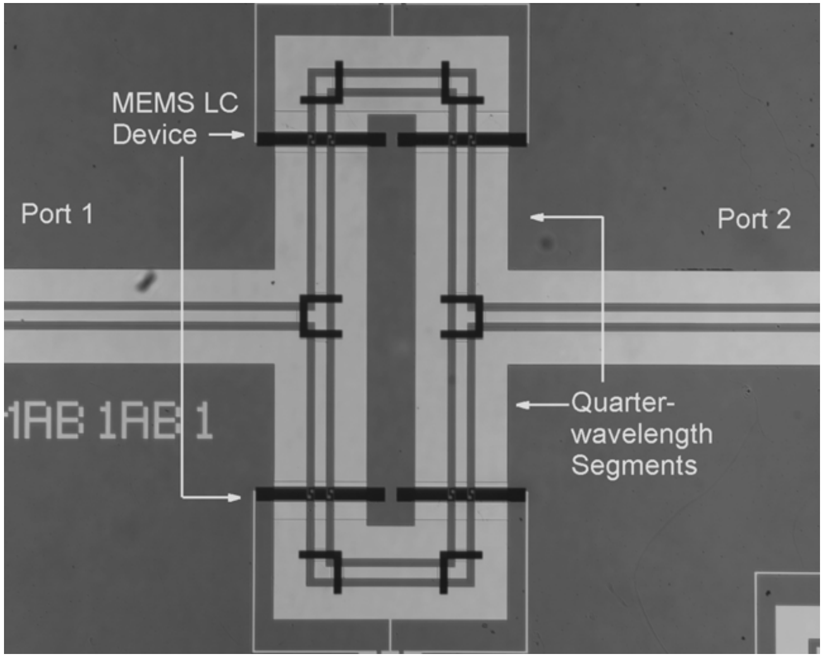
SPST

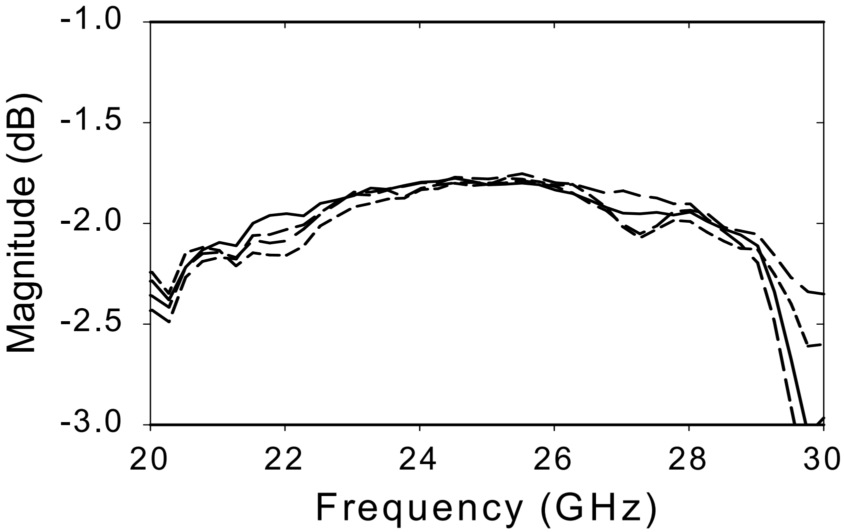


SPDT

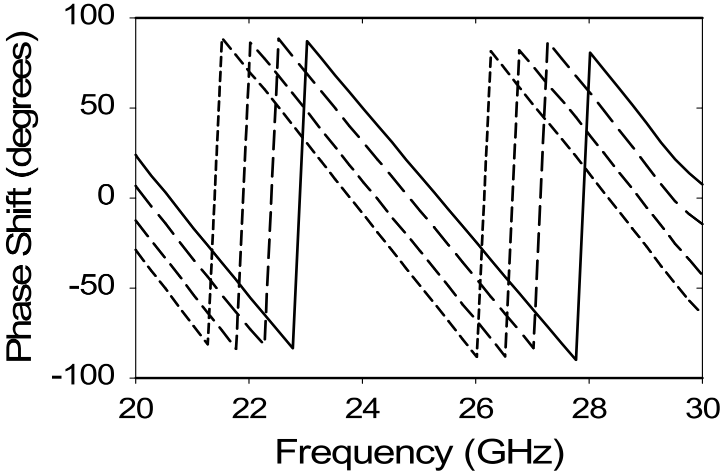


RF MEMS Phase Shifters on High-ρ Silicon





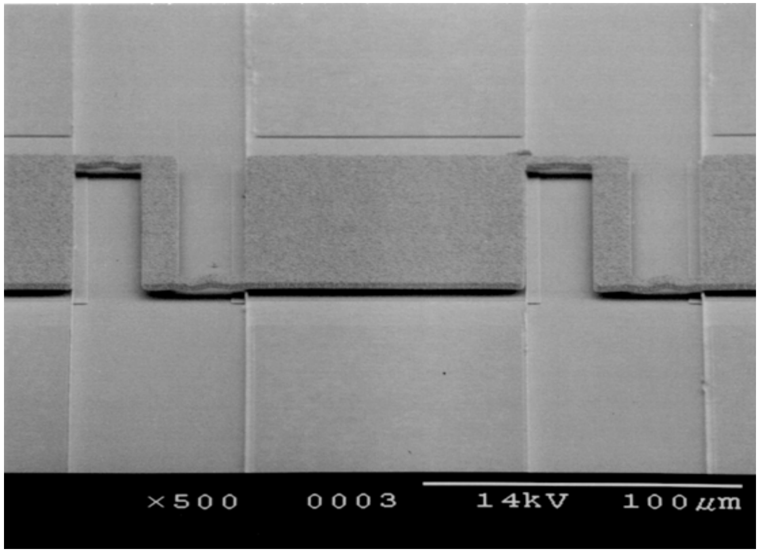
Insertion Loss for 2-bit shifter
~ 1.8 dB at 25 GHz

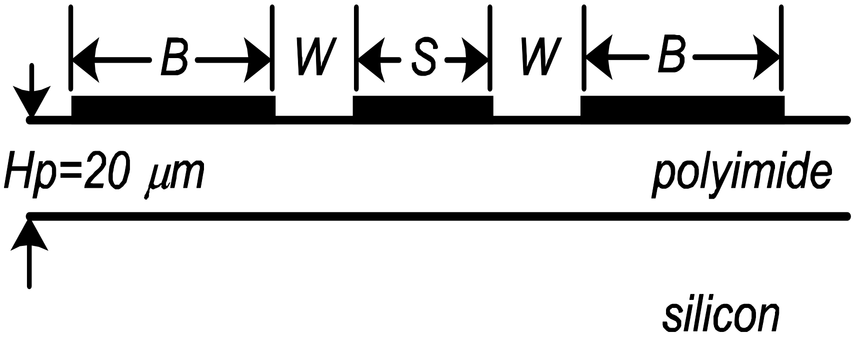


Phase shift for 2-bit shifter

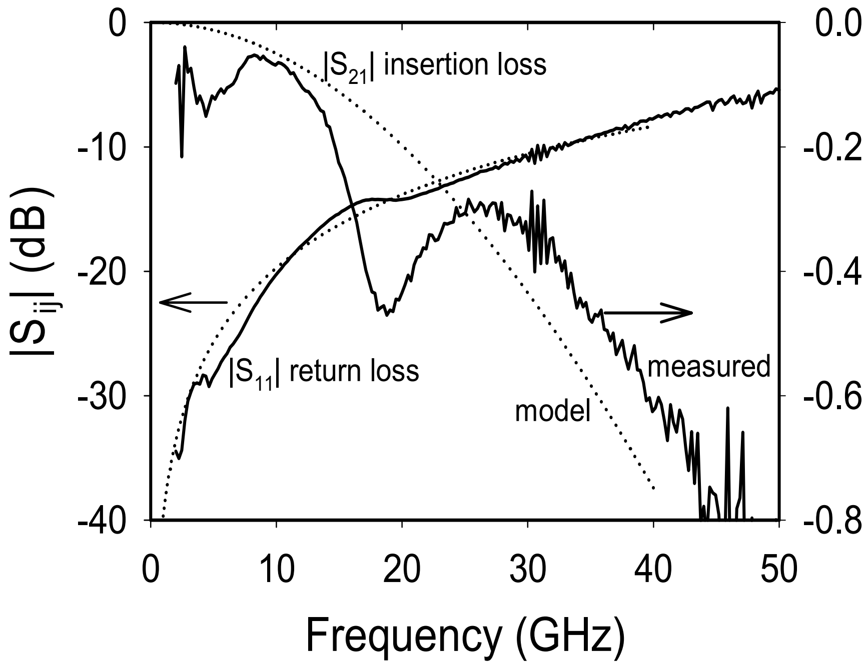
RF MEMS Switches on Low-ρ Silicon With a Polyimide Interface Layer

- Lower cost CMOS grade Si wafers
- Challenge: Substrate is very lossy at microwave frequencies
- Thin interface layer minimizes the substrate effect (polyimide, BCB)
- Finite Ground Coplanar (FGC) lines and Thin Film Microstrip (TFMS) lines have yielded good performance



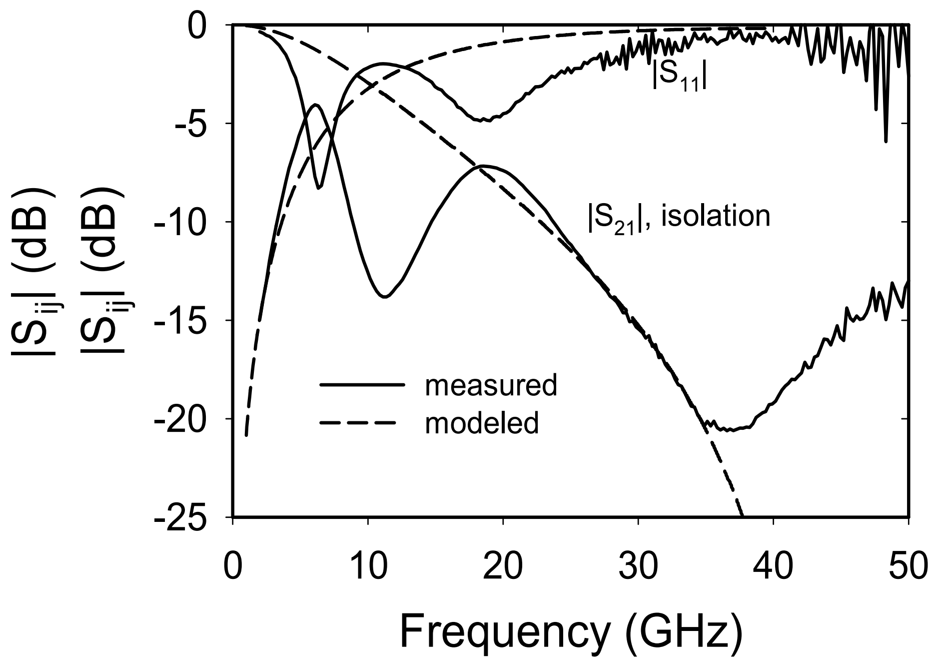


Results for switch on Low-ρ Silicon With a Polyimide Interface Layer



Up State

L=25 pH, C=66 fF, and R=0.5 Ω
Insertion Loss ~ 0.15 dB (0.35 dB due to line loss) at 35 GHz

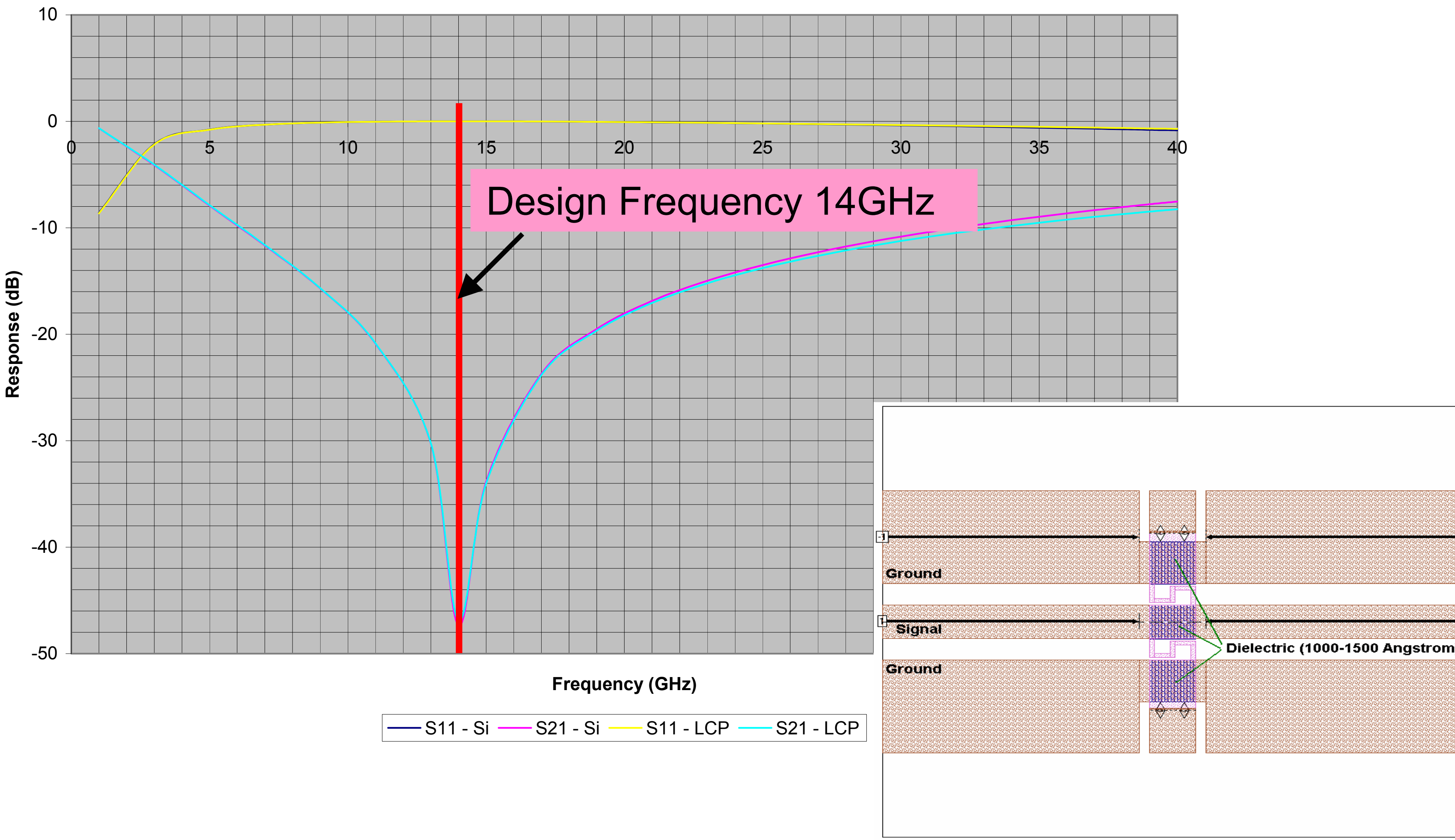


Down State

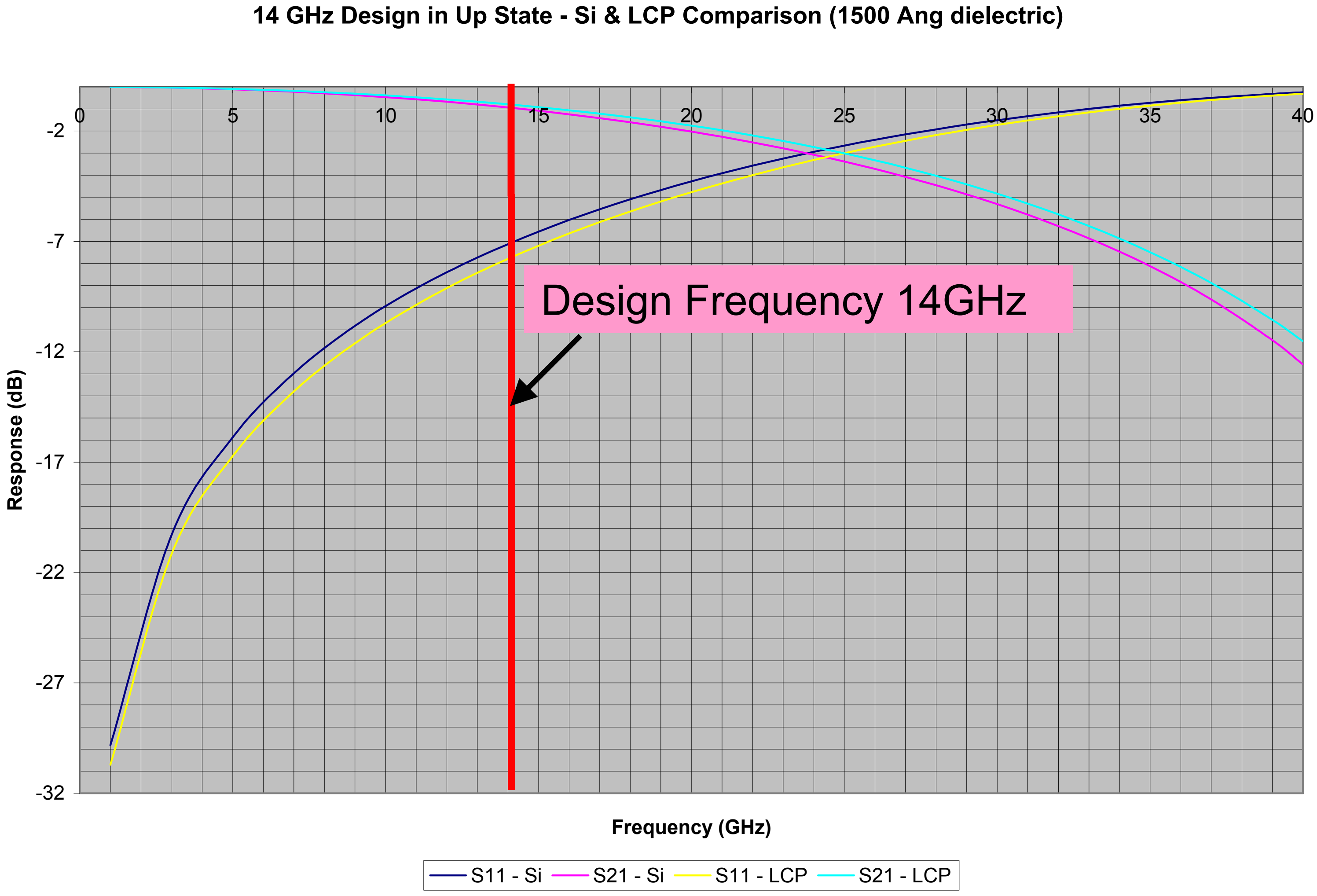
L=20 pH, C=580 fF, and R=0.5 Ω
Isolation ~ 20 dB at 35 GHz

14 GHz MEMS Switch

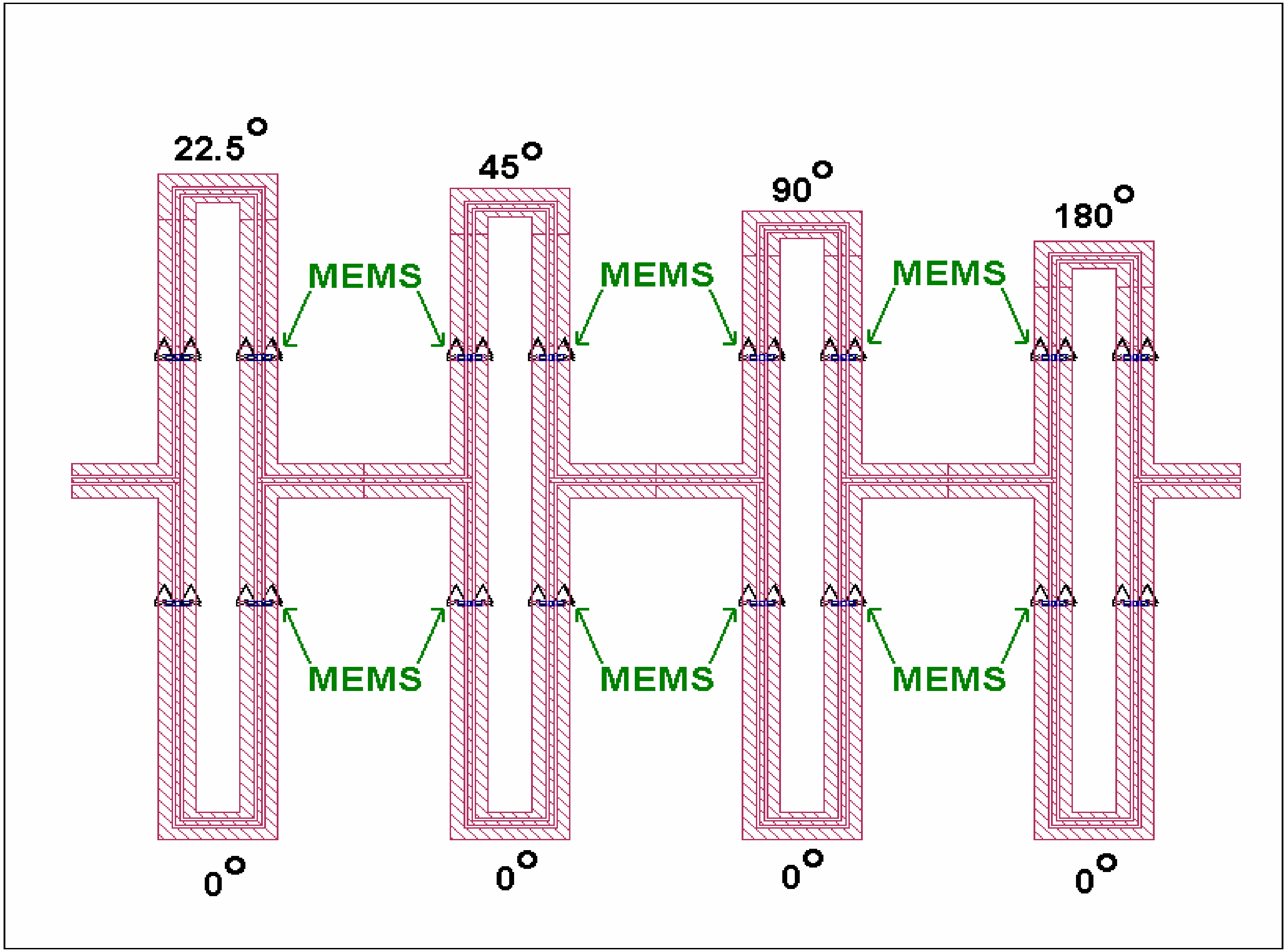
14 GHz Design in Down State - Si & LCP comparison (1500 Ang dielectric)



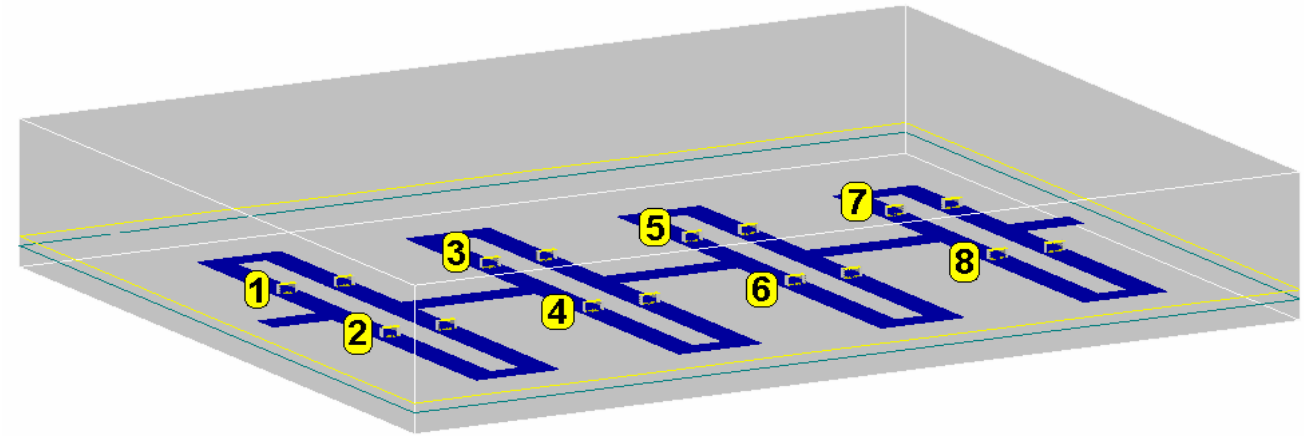
14 GHz MEMS Switch



14 GHz 4-bit Phase Shifter on 450μm Si



4-bit phase shifter simulated results



Ideal Phase (degrees)	Actual Phase	Signal Path (MEMS in UP State)	|S11| (dB)	|S21| (dB)
0	-1.45332	2-4-6-8	-9.761	-0.485
22.5	21.71488	1-4-6-8	-10.341	-0.421
45	44.38869	2-3-6-8	-9.631	-0.501
67.5	67.55689	1-3-6-8	-10.201	-0.436
90	89.22187	2-4-5-8	-7.909	-0.767
112.5	112.39007	1-4-5-8	-8.374	-0.682
135	135.06388	2-3-5-8	-7.803	-0.788
157.5	158.23208	1-3-5-8	-8.262	-0.702
180	178.98201	2-4-6-7	-3.948	-2.239
202.5	202.15021	1-4-6-7	-4.240	-2.053
225	224.82402	2-3-6-7	-3.881	-2.285
247.5	247.99222	1-3-6-7	-4.171	-2.095
270	269.6572	2-4-5-7	-2.951	-3.071
292.5	292.8254	1-4-5-7	-3.210	-2.819
315	315.49921	2-3-5-7	-2.891	-3.133
337.5	338.66741	1-3-5-7	-3.149	-2.876

Conclusions/Future Work

- Loss results of LCP up to 110 GHz confirm viability of material selection
- Preliminary array designs and return loss measurements exhibit very good performance
- RF MEMS switches and 2-bit phase shifter exhibit very good performance
- Continue characterizing LCP's tanδ from 2-110 GHz using ring resonator and microstrip structures
- Test array patterns at 14 GHz and 35 GHz
- Develop and characterize arrays with coupling slot feeding networks
- Design of 2x2 arrays
- Fabricate and test RF MEMS 4-bit phase shifter on Si
- Develop and characterize RF MEMS switch on LCP
- Packaging of the RF MEMS switches using LCP